Journal of the Royal Society of Western Australia

ISSN 0035-922X

CONTENTS

Page

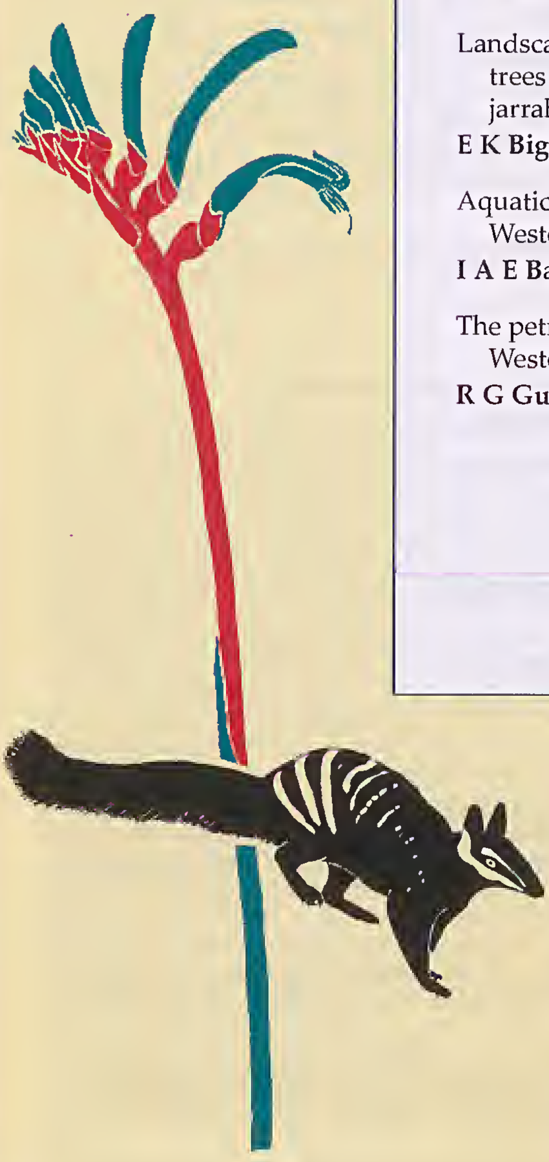
Dune slacks in Western Australia
C A Semeniuk & V Semeniuk 503

Influence of habitat characteristics on the distribution of the water-rat (*Hydromys chrysogaster*) in the greater Perth region, Western Australia
C Smart, P C Speldewinde & H R Mills 533

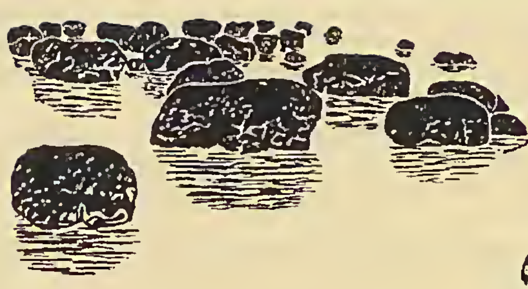
Landscape position predicts distribution of eucalypt feed trees for threatened black-cockatoos in the northern jarrah forest, Western Australia
E K Biggs, H C Finn, R H Taplin, & M C Calver 541

Aquatic invertebrates of rockholes in the south-east of Western Australia
I A E Bayly, S A Halse & B V Timms 549

The petroglyphs of the Kybra Aboriginal Site, South-Western Western Australia
R G Gunn, J Dortch, C Ogleby & A Thorn 557



Volume 94 Part 4
December 2011



The Royal Society of Western Australia

To promote and foster science in Western Australia

Patron
Her Majesty the Queen

Vice-Patrons
His Excellency Mr Malcolm J McCusker, AO QC
Governor of Western Australia

Professor Lyn Beazley AO FTSE MA PhD

The Royal Society of Western Australia was founded in 1914. The Society promotes exchange among scientists from all fields in Western Australia through the publication of a journal, monthly meetings where interesting talks are presented by local or visiting scientists, and occasional symposia or excursions on topics of current importance. Members and guests are encouraged to attend meetings on the third Monday of every month (March – November) at 7 pm, Kings Park Board offices, Kings Park, West Perth, WA 6005, or as advertised, in the RSWA Proceedings, Diary of Events.

Individual membership subscriptions for the 2011/2012 financial year are $75 for ordinary Members, $40 for Student Members and $40 for Associate Members. For Library, company and institution subscriptions see RSWA website http://www.rswa.org.au. Prices include GST. For membership forms, contact the Membership Secretary, PO Box 7026, Karawara, Western Australia 6152, or visit the website http://www.rswa.org.au.

The Journal of the Royal Society of Western Australia was first published in 1915. Its circulation exceeds 650 copies. Nearly 100 of these are distributed to institutions or societies elsewhere in Australia. A further 300 copies circulate to more than 40 countries. The Society also has over 350 personal members, most of whom are scientists working in Western Australia (see website http://www.rswa.org.au). The Journal is indexed and abstracted internationally.

Cover design: The four subjects symbolize the diversity of sciences embraced by the Royal Society of Western Australia. Mangles' kangaroo paw (*Anigozanthos manglesii*) and the numbat (*Myrmecobius fasciatus*) are the floral and faunal emblems of Western Australia, and stromatolites are of particular significance in Western Australian geology (artwork: Dr Jan Taylor). The Gogo Fish (*Mcnamaraspis kaprios*) is the fossil emblem of Western Australia (artwork: Danielle West after an original by John Long).

Dune slacks in Western Australia

C A Semeniuk & V Semeniuk

V & C Semeniuk Research Group
21 Glenmere Road, Warwick, WA 6024

Manuscript received July 2009; accepted November 2010

Abstract

This paper provides a review and revision of the term 'dune slacks' that was originally developed as a concept in the United Kingdom and Northern Europe. Using global and Australian case studies, we examine the types of dune slacks, their attributes, the range of their formational processes, and their evolution in relation to coastal setting, geomorphic processes and hydrology. Based on the processes and pathways of coastal dune development and evolution along the Western Australian coast and global variations, the original concept of dune slacks is expanded, particularly in the area of hydrological setting. Western Australia presents a wide range of coastal types, from rocky shores to depositional sandy coastal to tidal systems to erosional sandy coasts, to dune-dominated coasts, but dune slacks are found in only six sites, located mainly in the southwestern and southern regions of the State. They are developed at Whitfords, the Rockingham, Becher Point and Secret Harbour area, the Meerup/Yeagarup area, Reef Beach near Albany, the Warramurrup Dunes near Bremer Bay, and the Bilbunya Dunes in the Israelite Bay area. However, at some sites there are a range of coastal dunes settings wherein are developed different types of dune slacks. The Rockingham, Becher Point and Secret Harbour area, for instance, has depositional coastal settings to develop a dune slacks, and erosional coastal setting to develop β dune slacks. In this paper, the dune slacks of Western Australia are described in terms of regional setting, dune sand type and its $CaCO_3$ content, and dune slack water salinity and pH. Finally, the regional factors in Western Australia important for development of dune slacks, the occurrence of former dune slacks, and where dune slacks are not developed and why are described and discussed.

Keywords: dune slacks, coastal dunes, Western Australia, hydrology, coastal geomorphology, wetlands

Introduction

While a non-genetic approach to classifying wetlands at a site specific level, based on landform setting and hydrology, was emphasised by C A Semeniuk (1987) and Semeniuk & Semeniuk (1995), there is a place for a genetic classing of wetlands where there is a similar underlying pattern to their formation, *e.g.*, wetlands associated with dune formation, or with karst, or with development of fluvial landforms. A genetic approach to classification forms the basis to identifying wetlands of similar consanguinity, and hence to the identification of wetland suites (C A Semeniuk 1988). The category of wetlands, known as "dune slacks", has affinities with this latter type of classification, regardless of how they may be classified at the site-specific level, (*e.g.*, as seasonally waterlogged or seasonally inundated basins). This is not to imply that all dune slacks belong to the same consanguineous suite, or even that dune slacks along coastal Western Australia belong to the same consanguineous suite, but they do, in their own right, belong to a set or class of wetlands with important attributes in common, such as origin, setting, basin morphology and hydrological regime.

Generally, dune slacks are undescribed wetland systems along coastal Western Australia, though wetlands that can be classed as dune slacks have been noted, classified as site-specific types, or described by C A Semeniuk (1988, 2007) and Semeniuk *et al.* (1989). Dune slacks occur in Western Australia in Holocene coastal dune settings, extending from Whitfords in the central part of the Swan Coastal Plain on the western coast to Bilbunya on the southern coast, spanning a range of climate types and facing a range of oceanographic settings. This paper reports on their occurrence, variability, and formation in Western Australia, and adds to the global understanding of the variety of dune slack types and their climatic settings.

Western Australia provides opportunity for exploring the limits and definition of dune slacks. Unlike the geographically and climatically limited areas in northern Europe and the United Kingdom, where much of the early work on dune slacks was undertaken, or the local areas in South Africa, Uruguay, and Spain, which provided departures from the earlier concepts, Western Australia provides what is effectively a continuum of environments of coastal dunes with variation across this subcontinent. This variation is expressed in geomorphic setting, coastal dune and coastal landform development, and oceanographic, wind and other climate parameters, which progressively or discontinuously, alter the dune slack forming environments and the style of evolution the dune slack will undergo (or has undergone). In essence, Western Australia provides a classroom where the definition and limits of dune slacks can be investigated.

The first objective of this paper is to trace the origins, and provide a brief history of usage of the term "dune slack," to explore what constitutes wetlands in this category, and what defines the boundaries or range of the class. This paper also examines the present usefulness of the term in the context of the range of wetlands which occur in the coastal dune environment. One impetus for this review has been the growing number of wetland forming processes and settings, identified in coastal areas, which have been amalgamated under this collective term. A rekindled interest in the historic roots and applications of the term "dune slack" has prompted an assessment of its scientific meaning. As a basis to the discussion, reference is made to wetland types in coastal dune settings around the world, with a special emphasis on the coast of Western Australia. Figure 1 illustrates the processes and pathways by which the concepts contained in the United Kingdom and Northern European body of work on dune slacks may be expanded.

The second objective of this paper is to describe examples of dune slacks from Western Australia, which span humid to arid climates, high to low energy shorelines, and erosional and depositional coastal tracts. In a divergence from the traditional way in which dune slacks are characterised, that is a focus on vegetation, in this paper they are described from a geomorphic perspective, which includes and emphasises their setting, origins, underlying parent material, and their combined determinative effects on basic hydrological maintenance, all of which result in a particular wetland type.

This paper is based on extensive fieldwork and mapping. Dune slacks were identified during wetland mapping undertaken between 1980 and 2007 (V & C Semeniuk Research Group 1991, 1994, 1997a, 1997b, 2000, 2006, 2007, 2008). Aerial photography covering coastal Western Australia was used to identify sites for fieldwork, so that every major mobile coastal dune and beach ridge system was visited by helicopter or by road. In the field, sand was sampled from the dunes surrounding the slacks (as sediment parent to the slacks), and from within the slacks. Pits were used to sample groundwater and stratigraphy. Three of the sites in this paper were intensively studied between 1990–2004 (C A Semeniuk 2007), continuing at one site until 2010. Coring and laboratory description/analyses of sediments/soils follows Semeniuk & Semeniuk (2004, 2006) and C A Semeniuk (2007). Sediment was granulometrically analysed in 1 phi intervals, and calcium carbonate content determined by digestion in 10% HCl. Sediment, soil, and water were analysed at commercial laboratories for Ca, Na, K, Mg, N and P. At each wetland, plant species were identified and cover estimated. The term "dune field" is equivalent to the term "erg".

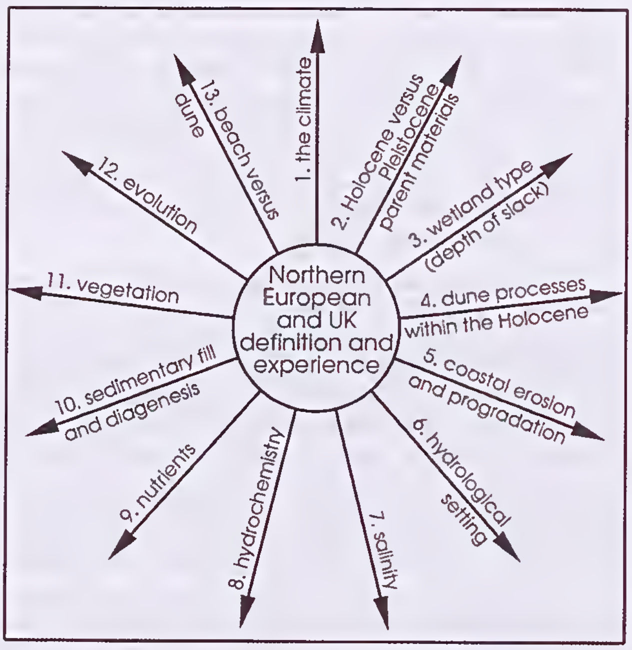


Figure 1. The thirteen possible settings, processes, and pathways by which the original concept of dune slacks, developed in the United Kingdom and Northern European, can be expanded.

Origin of the term "dune slack"

In the context of dune slack, the word slack comes from common usage, and derives from the Old Norse word "slakki" which originally meant a hollow on a hillside. In geographic areas where the Norse cultural influence persisted, including elements of the language, "slakki" became the etymological root for words for valleys or depressions in the ground. Over time, the term was applied to such valleys and depressions within the expanses of dunes which occurred in the central and northern coastal areas of the Netherlands, Denmark, Germany, England, Scotland and Wales. Often these valley sites were wet, in contrast to their surrounds.

Among the first uses of the term "slack" and "dune slack" in scientific literature were van Dieren (1934), Tansley (1949), and Ranwell (1959). In these works, "dune slack" had already been modified to mean a damp or wet hollow within a coastal dune terrain, where the water table was seasonally at or near the surface. Thus "dune slacks" became associated with coastal dunes, as distinct from wetlands associated with swales in other dune systems, such as desert linear dunes. They also were strongly linked to two hydrological mechanisms: 1) seasonal inundation or waterlogging, and 2) recharge resulting from the seasonal rise in the regional water table. These features served to separate them from lagoons, "dune lakes" and from remnant fluvial systems (Bayly & Williams 1973; Timms 1982; De Raeve 1987; Leentvaar 1997; Grootjans *et al.* 1998). The hydrochemical system in dune slacks commonly is fresh water, and the underlying parent material is generally nutrient-poor mineral sediment (Willis *et al.* 1959a, 1959b, Jones & Etherington 1971, van Dijk & Grootjans 1993, McLachlan *et al.* 1996; Lammerts & Grootjans 1997; Lammerts *et al.* 2001). Developmental processes in common with all types of dune slack include the input of salt spray, sand mobilisation, and incipient soil development within the basins (Lubke & Avis 1982).

It can be seen from this very brief summary that, with respect to some attributes, the initial general term "dune slack" had been modified in the scientific literature to have some very specific meanings. Firstly, the dune slack was not related to just any dune system, it referred specifically to a hollow in coastal dunes. Secondly, the term hollow was not just any hollow but one subject to seasonal inundation or waterlogging. Thirdly, the water

in the hollow should be maintained only by groundwater rise, and finally, the chemistry of the dune slack water should be fresh or evolving from brackish (*i.e.*, recently marine-derived) to fresh.

Types of dune slacks

Dune slacks are not as widespread as one would imagine. In coastal locations in similar latitudes, the most common general wetland forms are estuaries and deltas, barred estuaries and lagoons, coastal plains/tidal flats, or seepage lines in cliffed coasts (Bird & Schwartz 1985). Even in beach ridge and dune settings, which are conducive to dune slack formation, there are other types of wetlands, with no relationship to coastal processes and, in dune fields high above the water table, there may be no wetlands in the dune hollows. A further restriction on the definition and concept of dune slacks is the requirements for seasonal fluctuation of the water table and input of fresh groundwater, which suggest a temperate climate setting.

There were attempts by early researchers to identify various types of dune slacks with reference to the origins of their formation (van Dieren 1934), the plant communities within them (Crawford & Wishart 1966; Ranwell 1972), and some aspects of their chemical environments, notably the differences in pH in the groundwater and ion concentrations in the sediments. Van Dieren (1934) identified two types of dune slacks: primary and secondary.

"Primary dune slacks" form on prograding coasts where seaward advancement is rapid and plains of successive beach ridges and swales, beach flats, and spits comprise the coastal landforms. A short term change in offshore energy conditions or supply of sediment may see the recommencement of ridge building along the strandline, thus effectively creating a barrier between the already formed flat or swale and the sea, and cutting off the lowland from marine processes (C A Semeniuk 2007). The initial brackish character of the groundwater in the lowland is slowly replaced by the freshwater influence of a rising water table (Grootjans *et al.* 1998).

"Secondary dune slacks" are formed by wind erosion (van Dieren 1934; Ranwell 1959; Willis *et al.* 1959a, 1959b; Siljestrom *et al.* 1994; Grootjans *et al.* 1998; Yan *et al.* 2006). This can take place in an established and vegetated dune massif when a break in the dune plant cover becomes a node for erosion and for re-mobilisation of sand and construction of new dune forms and depressions, or it can occur when the coastal wind forms parabolic dunes and bowls (Short & Hesp 1982; Boorman *et al.* 1997).

Further differentiation of dune slacks using the traditional criteria of pattern of vegetation cover, physiognomy, and composition of wetland plant assemblages was practiced. Pioneer species, plant growth forms and community structure were used to separate younger and older dune slacks (Ranwell 1960; Crawford & Wishart 1966; Ratcliffe 1977; van der Meulen & van der Maarel 1993; Avis & Lubke 1996). Identification of the plant species as indicators allowed Ranwell (1972) to differentiate three categories of dune slack: dry, wet, and semi-aquatic, reflecting the average groundwater level over a period of time. This approach was subsequently adopted by other researchers (van der Laan 1979; Boorman 1993; Grootjans *et al.* 1995).

Differentiation between acid and base rich dune slacks has been approached in a number of ways. Kaiser (1958), cited in Leentvaar (1997), distinguished between acidic oligotrophic and neutral oligotrophic types, based on pH and calcium content of the water. Emphasis has been placed on acidic and base rich dune slacks in the United Kingdom as part of their conservation programme because of the effects of the groundwater and sediment chemistry on species colonization (Boorman 1993). Lammerts *et al.* (1992) and Grootjans *et al.* (1996) both demonstrated that calcium content in the water is a major determinant of dune slack plant community composition and sediment evolution in a humid climate, and C A Semeniuk (2007) described the gradation and alteration of highly calcareous to more acidic dune slack sediments in a temperate climate.

Already embedded in these early attempts at classifying dune slacks were the seeds of future classification problems. The term "primary dune slack" was applied to both coastal dune and beach settings. Differentiation between acidic and base rich slacks posed questions about slack evolution and the amount of peat fill which could be present in a traditional "dune slack". Recharge resulting from the seasonal rise in the regional water table, which had formerly been a fundamental attribute of dune slacks, was replaced by a reliance on plant species as indicators of dune slacks and dune slack types. This shift in focus overlooked the fact that the same plant community may colonise seasonal coastal dune wetlands whether they are recharged by groundwater rise, perching of rainwater, seepage, or fluvial input.

The range of formational processes and attributes of dune slacks

In spite of the previous comments upon classification, the scientific literature shows that the term "dune slack" was clearly understood by researchers in the United Kingdom and the Netherlands for a European setting. It immediately identified a group of wetlands with some fundamental similarities which could be used in comparative analyses, and inspired a repository of communal information which has been steadily built upon. It also facilitated international cooperation for the conservation of these wetland types and the rare plant species which characterise many of them. However, increasing research into coastal areas and wetlands outside the United Kingdom and the Netherlands brought to light wetlands in coastal dune settings which exhibited important divergences in geomorphic origin and history, settings, and hydrologic processes. Types of wetlands in coastal dune terrains elsewhere did not always conform to the categories of "primary" or "secondary" dune slacks, and those which did often developed more complex functions as they evolved. It is timely to determine whether the term "dune slack" is still appropriate for this extended range of wetland ecosystems by examining the ways in which these wetlands differ from those first described. The following features have been selected: setting, dune types, water regimes and hydrological mechanisms, and the effect of evolution.

Dune slacks, even initially, could be separated into distinct geomorphic settings:

- a depositional coastal setting associated with the construction of foredunes, beach ridges, beach spits or dune building, and
- an erosional environment of mobile dunes, sand sheets, blowouts and dune residuals.

The depositional setting is usually linked to coastal progradation. Spits and barriers associated with the widening of beaches and development of cuspate forelands, tombolos, estuaries and deltas enclose and separate shallow nearshore marine areas to form an ephemeral saline water body. Initially, this body is maintained by marine and tidal processes, but evolves over time, as progradation continues or as the seaward barrier becomes wider and higher, to a freshwater system, maintained by near surface groundwater. In this context, the lagoon or lake is relatively short lived and the phase approaching equilibrium is that of seasonal inundation. On prograding coastlines, a second type of "damp or wet hollow between the dune ridges, where the groundwater reaches or approaches the surface of sand" was identified by Tansley (1949). Examples commonly comprise wide beaches, backed by a foredune and successive dune ridges. The hollows between the low dune ridges and the beach foredune can have various geometric forms: a linear flat floored lowland, a linear to irregular depression filled with conical sand residuals, sand shadow mounds and hollows, or an irregular depression with single or multiple basins. Low lying areas that are close to the water table will form slacks. Depending upon the height of the land surface relative to the water table, inundation or waterlogging will occur. Such wetlands have variously been termed dune slacks (Chapman 1964; Dickinson and Mark 1994; Freitas *et al.* 2007), dune ponds, or dune lakes (Westoff 1954; Bayly & Williams 1973; Timms 1977), or wet swales (Wiedemann 1993; C A Semeniuk 2007). These wet basins are either seasonally inundated or waterlogged, depending on the configuration and position of the water table, relative to sea level and the land surface (C A Semeniuk 2007).

An offshoot of this common type of dune slack formation in a depositional setting, described only recently, is that of the intersection of inter-ridge swales by a rising water table in response to coastal progradation of a cuspate foreland and subaerial beach ridge plain (C A Semeniuk 2007). In this example, the constant is the beach ridge plain and the variable is the rising regional water table.

In contrast, dune slacks formed in comparatively stable (non-prograding) coastal settings, where aeolian erosion is the formative process, owe their wet origin to local exposure of the near surface water table and begin as a seasonally inundated basin evolving over time to a drier seasonally waterlogged basin. This exposure of the water table commonly occurs in association with dune migration and deflation of established dune systems (Lundberg 1993). However, there are variable internal factors inherent in this simple system of dune slack formation also. For instance, the surface exposed by wind deflation may not be composed of the same material as the dunes, or the deflation surface may lie at some considerable height above the regional water table, with the "slacks" in both situations relying on hydrological mechanisms other than inundation or waterlogging by seasonal regional groundwater rise, as described above.

Dune types can also determine the nature of dune slacks (Figure 2). Foredunes and beach ridges have been mentioned in relation to prograding shorelines, and parabolic dunes, chaots and conical hill residuals typify erosional shorelines (Semeniuk *et al.* 1989). However, in many coastal settings, transgressive (ingressing) dunes occur and can extend for considerable distances inland. When transgressive dunes climb established topography or become isolated inland from the main dune field, "intra-dunal slacks" exhibit different characteristics. The basement underlying this type of slack or depression may be bedrock, a calcretised or cemented layer of an older dune, or a buried pedogenic layer, with very different hydrological and hydrochemical properties from slacks underlain by beach or dune sands.

Natural and anthropogenic geomorphic processes can mirror each other in the formation of "dune slacks", but whereas natural processes are part of the present coastal wind and wave regime, and depositional and erosional products, anthropogenic processes, in fact, can occur at times and places which are unrelated and contrary to the geomorphic stage and evolution of the region. Stable vegetated dunes are the template for natural development of parabolic dunes and blowouts. Nodes, where vegetation is undermined and removed occur naturally in coastal systems subject to waves, storms, and persistent winds, initiate development of mobile transgressive dunes. However, dunes can also be destabilised when binding vegetation is removed through anthropogenically-induced effects such as erosion by vehicles, fire, or grazing. Under these latter processes, dune movement can be initialised and slacks may develop in what is no longer a current shoreline dune system, but as a palaeo dune system such as in the older dunes of Donana National Park, or King Island, Tasmania (Jennings 1957; Siljestrom *et al.* 1994).

Hydrological mechanisms and water regimes can also vary in different types of slacks. Although dune slacks are generally maintained by a near surface water table, the way in which this occurs can vary. Initially, it was thought that the regional water table was directly intersected and exposed in an inter-dune depression (*e.g.*, the convex profile of the water table described by Willis *et al.* 1959a, 1959b for Braunton Burrows in Devon, and by Ranwell 1959 for Newborough Dunes in Anglesey) or that it rose above the ground surface in response to seasonal rainfall as part of the regional hydrological pattern. However, dune slacks can be maintained through intersection of a local water table. For instance, a localised elevation of the water table can result when a coastal barrier impedes groundwater flow and causes mounding behind a barrier, or when the water table rises in response to overflow seepage from a barred river or barred estuary (Warren River, southern Western Australia). Further, a rise in the water table may result from causes other than rainfall, *e.g.*, the water table rise in response to coastal progradation and a gradually falling sea level (C A Semeniuk 2007).

In addition, there have been descriptions of local low inter-dune areas where rainwater is perched on near surface relatively impermeable peat or clay layers (Bakker 1990, C A Semeniuk 2007). In these examples, the dune

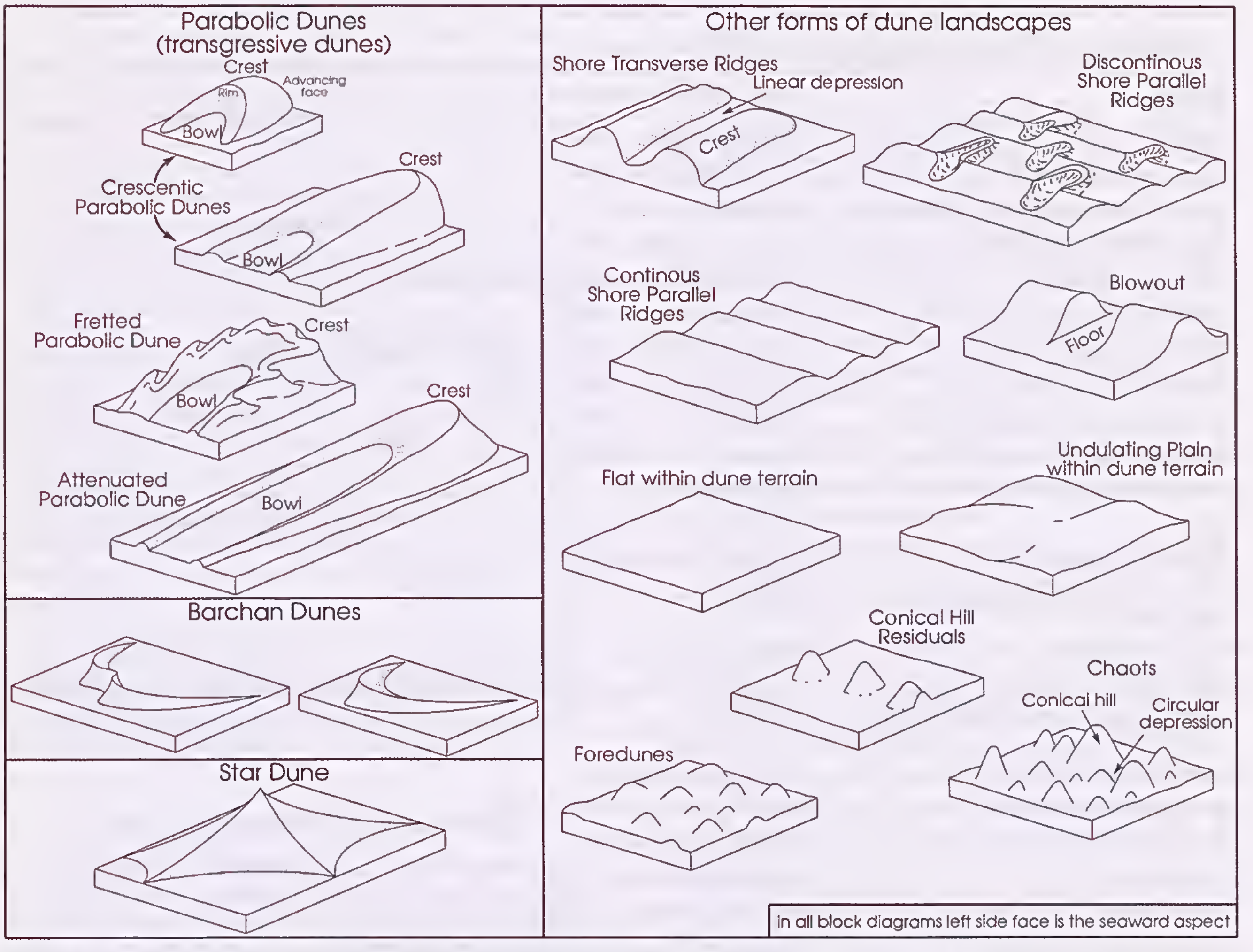


Figure 2. The variety of dune landscapes within which dune slacks can be developed (modified from Semeniuk *et al.* 1989, and with addition of star dunes and barchan dunes). The lowlands in all these dune landscapes, if they intersect the water table, can potentially develop dune slacks.

slack generated *in situ* sediment and this has determined the variation in hydrological style. In addition, there are slacks which owe their wetness to surface or near surface perching or ponding of rainwater, not on intra basin fills generated *in situ,* but on basements and pavements underlying the dunes exposed by wind deflation.

Dune slacks in the Netherlands and Britain are maintained by fresh to brackish water, but groundwater in other climatic zones may not be fresh. When slacks were described in arid coastal dunes settings in the north of Africa and the Middle East, as having mesosaline (sea water concentration) to hypersaline waters, many scientists responded by implicitly excluding these wetlands from the definition of dune slacks. Similarly, dune slacks, which are permanently inundated, and consequently deeper, have been alternately termed dune lakes or lagoons, depending on their stage of development. This has been the case even when the slacks are maintained by the rise in the regional water table. Therefore it must be deduced that the seasonality of rainfall and the height of the groundwater rise are important hydrological criteria for dune slacks.

Dune slacks may be acidic or base rich, as determined by their groundwater and sediment chemistries, but are generally nutrient poor. The short development period, constant shifting or infilling of the basins in a dynamic dune environment, and the low density and productivity of plants, generally result in lack of organic matter accumulation in the basins.

Where dune slacks are well developed, they are often subdivided on the basis of the underlying parent material, either relatively acidic siliceous sands, quartzose calcareous sands with 1–5% carbonate, or calcareous sands with up to 95% carbonate content (Table 1). Where mixed quartzose/calcareous sand is present, the calcareous component of the sand is often minimal to begin with, and in this type of setting, decalcification has been shown to quickly reduce the amount of calcium carbonate (Tansley 1949; Ovington 1951; Salisbury 1952; Ranwell 1959; Carter & Wilson 1988; Moreno-Casasola 1988; van Dijk & Grootjans 1993; Grootjans *et al.* 1996; Crawford & Wishart 1966; Munoz Reinoso 2001; C A Semeniuk 2007).

The presence of calcium carbonate in the groundwater and in the underlying sediment results not only in a unique style and rate of sedimentation but also in a chemical environment which determines the unusual biotic response of rare flora and inter-annual variation in species composition (Grootjans *et al.* 1998; C A Semeniuk 2007).

Table 1

Examples of dune slack sites with siliceous or calcareous parent sands

Location	Dune slack parent material
Finland	Siliceous (Hellemaa 1998)
Lista & Jaeren (Norway)	Siliceous (Lundberg 1993)
East and west Frisian islands (Netherlands)	Siliceous (Westoff 1989)
Sands of Forvie, Aberdeenshire, (Scotland)	Siliceous (Boorman 1993)
Barry Links (Scotland)	Siliceous (UK Nature Conservation site 2009)
Torrs Warren, Dumfries (Scotland)	Siliceous (Boorman 1993)
Studland Dunes (England)	Siliceous (Chapman 1964; UK Nature Conservation site 2009)
Winterton, Norfolk, (England)	Siliceous (Boorman 1993)
Coto Donana National Park (Spain)	Siliceous (van Huis 1989)
Southwestern Iberian coast, (Portugal)	Siliceous (Freitas *et al* 2007)
Turner's Peninsula (Sierra Leone)	Siliceous (Scott 1985)
Nigeria	Siliceous (Usoro 1985)
East and southeast South Africa	Siliceous (Tinley 1985a)
Zambezi Delta, Maputaland Dunes (Mocambique)	Siliceous (Tinley 1985b; Botha & Porat 2007))
Malaysia Peninsula	Siliceous (Teh 1985)
Eastern Australia (Frazer Is., Newcastle, Myall Lakes, Qld., eastern and western Victoria)	Siliceous (Thompson 1981; Timms 1977, 1982, 1986, 1997; Bird 1985; Outridge *et al.* 1989; Ward 2006)
West King Island (Tasmania)	Siliceous (Jennings 1957)
Haast Ecological District (NZ)	Siliceous (Dickinson & Mark 1994)
Polonio's Dunes (Uruguay)	Siliceous (Jackson 1985)
Tabasco (Mexico)	Siliceous (Castillo *et al.* 1991)
Southern Brazil	Siliceous (Cordazzo & Seeliger 1988)
Newborough Warren (Wales)	Quartzose/calcareous sand 1–3 % (Ranwell 1959)
Isle of Man (England)	Quartzose/calcareous sand 2–3% (UK Nature Conservation site 2009)
Noord-Holland (Netherlands)	Quartzose/calcareous sand .05–80% (Rozema *et al.* 1985)
The Delta (Central & southwestern Netherlands)	< 10% calcium carbonate (van der Meulen & van der Maarel 1993)
Brittany and Normandy (France)	Quartzose/calcareous sand <35 % calcium carbonate (Beeftink 1977)
Magilligan beach ridge plain (Eire)	Quartzose/calcareous sand 11.7–5.5 % calcium carbonate (Carter & Wilson 1988)
Braunton Burrows (England)	Quartzose/calcareous sand (Willis *et al.* 1959a, 1959b; UK Nature Conservation site 2009)
Cumbria (England)	Quartzose/calcareous sand (UK Nature Conservation site 2009)
Northumberland Dunes (England)	Quartzose/calcareous sand (UK Nature Conservation site 2009)
Sefton Coast (England)	Quartzose/calcareous sand (UK Nature Conservation site 2009)
Kenfig Burrows, (Wales)	Calcareous (Jones & Etherington 1989; Boorman 1993)
Gower, Oxwich, (Wales)	Calcareous (Boorman 1993)
Saltfleetby, Lincolnshire,(England)	Calcareous (Boorman 1993)
Sandscale, Ainsdale, Lancashire	Calcareous (Boorman 1993)
North of Bergen aan Zee (Netherlands)	< 1 % calcium carbonate (Rozema *et al.* 1985)
South of Bergen aan Zee (Netherlands)	< 15 % calcium carbonate (Rozema *et al.* 1985)
Flemish coastal plain (Belgium)	Calcareous content frequently 10 % (De Raeve 1989)
Libya	Calcareous sand >90% calcium carbonate (McKee & Ward 1983)
Western India	Calcareous sand >90% calcium carbonate (Skudder *et al.* 2006)
Alexandria dunefield (S. Africa)	Calcareous sand (McLachlan *et al.* 1996)
East King Island (Tasmania)	Calcareous sand (Jennings 1957)
Yucatan Peninsula (Mexico)	Calcareous sand (Espejel 1987)

Evolution of slacks further complicates the definition and understanding of the term "dune slack". Initially, the term carried with it an implication of impermanence. Many individual slacks were short term features lasting between 50 and 100 years, and were replaced during the ongoing processes of dune erosion and sand mobilization, or alternatively by the continual development of spits or beach ridges. However, in some cases, either the progressive infilling did not occur, or the dune slacks became deeper over time, and remained a longer term feature in the landscape. In these wetlands a new sedimentary fill accumulated, such as peat or organic ooze, or carbonate mud, differentiating them from primary dune slack sediments, and generating distinctive geochemistry, hydrochemistry, hydrological processes and plant communities (Schat 1984; Sival 1996; Sykora *et al.* 2004; Grootjans *et al.* 2008). As the wetlands passed through alternate phases of relative humidity and aridity, during the Holocene, the accumulated intra-basin sedimentary deposits began to exert an independent influence on the fluctuating water table, in some cases disrupting the seasonal vertical movement of the groundwater.

To continue this discussion, some examples of dune slacks in unusual settings, or with complex histories or functions are described below, in order to further illustrate the body of diverse coastal dune wetlands which have been described as a "dune slacks."

Global and Australian case studies

Primarily, and historically, dune slack development and maintenance have been related to coastal processes. The initialization of dune slacks, through reactivation of stabilised dunes due to disturbance and loss of vegetation cover, brings to the fore several important questions regarding dune slack formation and classification. What is the precise meaning of "coastal dune" when applied to dune slacks? Where a sequence of coastal dunes is present, the oldest of which now extend some distance inland, are the wet hollows in all the dunes correctly termed dune slacks? What separates true dune slacks from wetlands occurring within any other type of dune field?

Historically, dune slacks manifest relatively simple hydrological mechanisms and stratigraphic fills. However, what commenced as a dune slack may, if it survives, evolve into a different type of wetland, often with an increase in the internal complexity of features and functions. Straight forward examples include: 1) the accumulation of wetland fills whose composition is sufficiently distinctive from the original dune slack to influence geohydrological processes and geohydrochemical reactions; and/or 2) basin deepening over time, due to tectonic, hydrological or biological processes, which causes the hydrological regime to shift from seasonal to permanent inundation, or increases the number of mechanisms which recharge the wetland. Evolution may eventually produce a wetland with little in common with what is currently termed a dune slack. Another question relating to time concerns the age of a dune slack. Dune slacks are considered to be recent phenomena, integral to the dominant extant coastal land-forming processes. Once a dune slack becomes established, when does it become too old or too isolated to conform to the criteria of the wetland group? Several examples are described below.

An example of a complex situation in which there are dune slacks is the Donana National Park, southwest Spain. Donana comprises estuarine, littoral and aeolian systems (Siljestrom *et al.* 1994) which are the result of cycles of coastal progradation interspersed with erosion during the Holocene. The aeolian system, which consisted of wind reworked material eroded from a Pliocene-Quaternary coastal cliff and transported by southeast littoral drift, commenced during the third cycle of coastal history, 2500–1000 years BP (Siljestrom *et al.* 1994; Rodriquez-Ramirez *et al.* 1996). There are two recognizable Holocene dune terrains:

1 that characterised by the three older sequences, inland from the coast, comprising stable dunes, the most recent of which has parabolic dune forms and well delineated slacks, and

2 that characterised by the two younger sequences located at the coast in the 4 km narrow strip of active shoreline (Munoz Reinoso 2001).

Both sets of dunes contain wetland basins. In the undulating landscape of stable dunes, a rising water table creates "lagunas," temporary water bodies, when it intersects the topographic hollows. The current active dunes exhibit four well delineated dune fronts with linear wet and dry slacks between them (Siljestrom & Clemente 1990). The slacks are regarded as discharge zones for groundwater from the dunes, and the water tables lie approximately 0–0.5 m below the surface for wet slacks and 2.0 m for dry slacks. The dune slacks were all formed during the Holocene, at the coast, and through similar processes. They are maintained by groundwater and are seasonally inundated or waterlogged.

However, the "lagunas" are no longer directly influenced by coastal processes. The only coastal influence is the receiving of airborne marine salts. Hydrologically, they are recharged by rainfall, runoff and groundwater discharge, but these flows respond to localised topographic features and pathways (Serrano *et al.* 2006). In other words, they are developing independent local catchments and internal recharge pathways, and the trend is towards a more closed and internal hydrological system than the open-ended one in the dune slacks of the active dune terrain.

A similar example occurs in King Island, Tasmania (and, potentially, along any coast where several sequences of dunes occur). In King Island, two groups of dunes have been identified: "Old Dunes" and "New Dunes" (Jennings 1957). Slacks in the bowls of the parabolic dunes are present in both systems, but are better developed and more common in the "Old Dunes". The reasons proposed by Jennings to explain this distribution are linked to evolution of the landscape. Firstly, the denuded thinner "Old Dunes" (quartz sand dunes) lie close to sea level, facilitating intersection of the land surface with the regional water table; and secondly, development of a slightly semi-permeable layer of iron cemented humic sand known locally as "coffee rock", a diagenetic product linked to water table fluctuations, perches water in the bowls of the "Old Dunes", thus effecting wetland development. Neither of

these processes is likely to be associated with young dune slacks.

Holocene dune fields west and east of Esperance on the southern coast of Western Australia provide examples of dune slacks and dune hollows formed in an erosional setting. The Esperance region comprises an inland plain (the Esperance Plain) which, towards the coast, gives way to a terrain of gneissic and granitic monadnocks surrounded by Tertiary and Quaternary sediments, eroded back to form a coastline of granitic headlands and islands interspersed with curved bays (Brocx & Semeniuk 2010). Sand transported along shore is reworked by prevailing winds into massive dune fields of parabolic, star, and barchan dunes, and slacks. The variety of mobile coastal dunes in this region provides opportunity to explore the limits of what constitutes a "dune slack".

At Butty Head, west of Esperance, the coastal dunes are mobile and sparsely vegetated star dunes, comprising yellow quartz sand. Buried soils are exhumed in the bowls of the dunes. In winter, the exhumed soil becomes moist but not saturated sufficiently to form wetlands. Hence, though there are dune hollows, there are no dune slacks. At Esperance Bay, the mobile dunes are underlain by a Holocene stranded higher-level beach deposit cemented as a sheet forming a pavement (at the once higher position of a water table). Locally, the cemented sheet has been breached, forming small mesas, and intervening 1.5 – 2 m deep hollows, exposing the water table. Although the entire dune and wetland complex is in a parabolic dune field, the wetlands are not dune slacks, as they are fixed features in an eroded "limestone" terrain. In the parabolic dunes at Rossiter Bay, the regional water table generally is too deep to initiate development of wetlands. However, near the coast, the bowls of the parabolic dunes intersect water flowing along a subsurface pavement sloping shorewards developed on the sediments of the Plantagenet Group, and becomes seasonally inundated when flow is taking place. The wetlands here overlie an unconformity, and not coastal dune stratigraphy, hence are not dune slacks. At Bilbunya Dunes, at the back of a wide beach, between the chaots or conical hill residuals, dune slacks occur where the freshwater water table is close to the surface. Inland of this chaot dune terrain, there are barchan dunes and star dunes, underlain by white sand with yellow and brown quartz sand at depth, with superimposed bounding surfaces and/or truncation planes between successive dune sequences. The hollows and flats, between the dunes, intersect the seasonal water table perched on the bounding surfaces, creating ephemeral wetlands which can be categorised as "dune slacks".

In each of these examples of dune fields in the Esperance region, the basement under the coastal dunes is different: buried soil; a cemented sheet; slightly muddy yellow sand, a relatively impervious bounding surface; Pleistocene limestone; a laterite sheet overlying Plantagenet Group; sediments of the Plantagenet Group; and unconsolidated beach sand. In each situation, the basement affects aspects of the hydrology, such as the flow of groundwater, the access to it, and its duration, depth, and chemistry. Where dune slacks are developed, the wetland substrates comprise the same material as the parent sand, *viz.* colour mottled, fine, homogeneous, quartz sand, and therefore, sediment storage capacity and the height of the capillary fringe are generally constant. In each of the dune slacks in the Esperance region, there are differences in the density and composition of the plant cover, reflecting the hydrological effects of the different basements, from compacted to unconsolidated types.

Evolution of dune slacks

Evolution takes place in all landscape features and, in relation to dune slacks, may be expressed in the following ways:

1. evolution of the landform setting,
2. evolution of the geomorphology of the wetland basin itself,
3. evolving number and style of hydrological processes,
4. increasing complexity of the hydrochemistry,
5. changes in composition of the accumulating sedimentary fill,
6. geochemical and diagenetic changes, and
7. changes in nutrient content of the wetlands.

Many of these processes are interrelated and one process can initiate or accelerate a second process which may then cause further inter-reactions. A simple example of this is the plant-induced precipitation of interstitial calcium carbonate cement in the vadose zone, which over time accumulates to become an impermeable subsurface layer. This layer then can perch subsurface infiltrated rainwater which makes more water available to plants, and seasonally saturates the sediment above the layer. Plants respond by increasing their productivity and biomass resulting in accumulation of peat which has a different effect on the hydrological properties of the sediments. Although some aspects of interaction will necessarily be referred to in the ensuing discussion, the aim of this section is to try to isolate each of the more common evolutionary aspects of dune slacks.

The most important evolutionary changes in the coastal dunes landform setting pertain to processes which result in either 1) coastal dunes and dune slacks being displaced from the coast by coastal progradation, or 2) hinterland dunes being intersected by coastal erosion. Progradation of the coast may result in coastal dunes, which formerly supported dune slacks, being cut off and isolated from coastal processes. Active dune formation ceases, and dune stabilization allows other mechanisms to come into play and/or to dominate. Landform stability gives plants the opportunity to change their own chemical and sedimentary environment, and provides an opportunity for diagenesis of intra-basin sediments, changing the ways in which water moves, or is stored within the basin. In this case, what were once dune slacks will become increasingly influenced by internal wetland processes (hydrologic, biotic, and chemical activity) tending towards different types of coastal wetlands. Coastal retreat may result in older stabilised dunes being reworked by waves and wind to become modern coastal mobile dune fields, or in the building of dunes on top of an older landform such as a stabilised dune field, planar plateau surface, or alluvial fan. In these latter examples new dune slacks may or may not be created.

Evolution of wetland basin geomorphology usually involves infilling of wet hollows, or the disappearance of ephemeral wet slacks, that occurs naturally in a dynamic dune environment, but may also involve common geomorphic modification such as a change in basin size or shape. A simple example relates to dune slacks in beach-parallel swales which become partitioned into smaller basins by the development of ingressing small parabolic dunes.

Hydrological change is inherent in dune slack developmental history. Shallow lakes change over time to seasonally inundated basins and, eventually, most become seasonally waterlogged basins. In some cases, dune slacks in the bowls of parabolic dunes begin as seasonally waterlogged or inundated basins and persist over time to become shallow lakes through mechanisms such as a rising, or mounded or perched water table.

The evolution of dune slack hydrology is dependent on two major determinants: climate and the nature of the hydrological changes. Dune slacks occur most typically in temperate settings where water availability determines their depth, size, chemistry, sedimentary fill, and biotic response. If rainfall in a temperate climate were to decrease, the size and distribution of the slacks may change, but the processes which are responsible for dune and slack formation theoretically could continue. Longshore drift, wind deflation, coastal erosion due to storms, and construction of spits, berms, beach ridges, and dunes could still continue to develop and shape dune fields. Dune sequences at Donana National Park and Esperance are examples of this. The major changes to dune slacks in this scenario will relate to hydrochemistry.

If rainfall were to increase over time in a temperate climate, the most common evolutionary changes would result in a rise in the water table, and to the depth and duration of surface water. The abundance of water may increase the density of plants, and the volume of above and below ground plant biomass and, over time, the accumulation of un-decomposed plant material as wetland fill. The major changes in the dune slacks in this situation will also be hydrochemical and geochemical.

Three hydrological changes have been identified which can shift the functions typical of dune slacks towards a more, or less, complex stage of development, or an alternate evolutionary pathway: 1) input of additional water from another source; 2) breaching of a seaward barrier; and 3) a rising, or falling, of the water table. Input of water from another source is most likely to occur through streamflow, deriving from natural fluvial migration, or anthropogenic drainage design stream capture, or channel redirection. A natural and relatively common example is dune building obstructing an estuary or river, and forcing channel switching, or mounding, and seepage, which can potentially increase the normal volume of groundwater in local pockets in downslope coastal areas where the dune slacks are located. In this setting, the additional water may alter the sedimentology, hydrochemistry, and water regime, thus increasing the complexity of the processes and the wetland products.

The second hydrological change listed, that of breaching of the seaward barrier, inundates the former terrestrial wetland, transforming it back to a marine condition, thus reverting to a less complex state.

A rise, or fall, in the water table within what is already a dune slack can be due to regional, local, or intra-basinal factors. For example, a rise, or fall, in the dune slack water table may be 1) part of a regional response to cyclic changes in rainfall patterns, progradation or erosion of the beach, or a changing sea level; or 2) due to a set of environmental conditions within a local area such as impounding of groundwater, local seepage, or the barring of a valley tract; or 3) a response to intra basinal conditions. Regional changes are likely to have a much broader effect on dune slacks than the increase or lowering of the wetland water table. Climatic and coastal changes are likely to include landform remodeling, changes to sediment distributions and volumes, and changes to the style, cyclicity and dominance of erosional and depositional mechanisms, and therefore, clearly the nature of dune slacks will change. Local changes in the water table may increase or decrease recharge to the dune slacks. The changes to water availability and volume may be large enough to result in evolutionary changes to the dune slack, or small enough to be assimilated into the range of hydrological conditions to which the wetland is tolerant. Changes to hydrology brought about by internal stratigraphic or biotic factors do tend to shift hydrological functions from open regionally dominated dune slack processes to more closed intra basinal wetland processes. In addition to the hydrological mechanisms of groundwater fluctuation and through-flow, which typify dune slacks, development of intra-basinal sediments and soils and conduits create preferential recharge and flow paths, changes to sediment type which increase or decrease porosity and permeability, and influence wetland hydroperiod, and rainwater perching takes place on surface or subsurface sediment layers.

In a temperate climate, dune slack hydrochemistry can be the derivative of one or more of the following processes: regular input of marine salts; seasonal input of slightly acidic rainwater; throughflow of slightly acidic groundwater from quartz-rich aquifers, or calcium and carbonate-rich waters from calcareous aquifers; and evapo-transpiration. Hydrochemical evolution of a dune slack typically involves a change from seawater to brackish water to fresh water. In a shift to more arid climates, the water deficit and evapo-transpirative regime may concentrate and precipitate salts, potentially leading to evaporite sedimentation and hypersaline ecology. In a shift to more humid climates, water surplus may increase the acidity and nutrient concentrations of groundwater, and deplete any calcium carbonate in the coastal sands underlying the dune slack.

Dune slacks can accumulate a variety of sedimentary fills: calcium carbonate mud (calcilutite), gypsum or salt evaporites; aeolian sand of quartz, quartz-carbonate, or carbonate composition, humic quartz sand, organic matter, and mixtures of these sediments. As plant cover increases in density, dune slacks often evolve to become dominantly peat-filled. It is not unusual for dune slacks to change the composition of wetland fill in response to relatively short term increases and decreases in regional rainfall, and so their sedimentary fills can exhibit complex stratigraphy with contrasting compositional layers (C A Semeniuk 2007). The existence of individual dune slacks with such variable sedimentary layers indicates that sediment fills across the range reflect evolving and/or changing dune slack ecology.

Diagenetic overprints on dune slack sediments deriving from groundwater movement and geochemical/ hydrochemical interactions between the plants, sediments, and groundwater include: textural changes in the sediment, increased hydration of sediments, leaching of salts and nutrients from the sedimentary profile, removal and transportation of the iron oxide coating to sand grains, dissolution of calcium carbonate, and precipitation of carbonate-cemented sands. Many of these processes are typically found in dune slacks (Grootjans *et al.* 1996; C A Semeniuk 2007). In most cases the effects will be minor, but if diagenetic alteration of the sediment permanently alters the dune slack hydrology, this must be viewed as heralding a new stage of wetland development. Such changes could come about through prolonged waterlogging which could result in changes to the texture and fabric of the dune slack sedimentary fill. The diagenetic alteration of grain size and packing brought about by grain dissolution, and reducing sand sized grains to mud sized grains, would increase the density and altering the packing structure of the sediment. The effect may be sufficient to increase seasonal inundation to permanent inundation. This hydrological change would fundamentally alter the wetland type from dune slack to freshwater dune lake and, also, its subsequent developmental path.

A second example of diagenetic effects involves interstitial precipitation of calcite within the vadose zone of the sediment profile to form a partially or fully cemented impervious sediment layer. Wetland hydrology then can be perturbated in several ways: 1) by prolonging the hydroperiod of the dune slack, 2) by increasing the depth of the surface water inundation, or 3) by moderating the water table fluctuations. The first two responses mimic the effects of a rise in the water table. Under certain conditions, the third response simulates a fall in water level. If seasonal rainfall is relatively low, or its frequency changes, there is the potential that there will be insufficient water to independently saturate the near surface sediments and that the seasonal water table rise will be impeded by the "hardpan", thus reducing overall recharge to the wetland.

Low levels of nutrients in groundwater and sediments characterise many dune slacks. Salts, resulting from evapo-transpiration and plant decay, are often removed seasonally by groundwater infiltration and through-flow, so that there is little buildup in the sedimentary profiles. This constant down-profile leaching and exportation of salts from the dune slack is one of their key characteristics in the United Kingdom and Europe. Dune slacks may be found exhibiting every gradation in geochemical composition of their underlying (dune) sands, from 90% calcium and magnesium carbonate content to < 10 % carbonate content in the surface layers with 90% carbonate content at the base of the wetland fill, to <10 % carbonate content throughout.

Given the basic premise is satisfied, that is, dune slacks form in coastal settings in response to erosion and deposition, sediment transport via littoral drift, beach widening, and wind deflation associated with mobile dune development, climatic effects may be incorporated into the category of dune slacks as variations (*e.g.*, expressed as freshwater *versus* brackish water types). However, when climatically induced changes evolve to the point where the mechanisms which maintain the slack become independent of the surrounding setting and become dominantly intra-basinal, they can be perceived as having evolved beyond the conditions that support dune slacks. It follows that any fundamental changes to the ways in which dune slacks function hydrologically may effectively be set as one of the limiting factors to delimiting of dune slacks. In other words, dune slacks are coastal dune wetlands which are dominated by external geomorphic, sedimentological, and hydrological processes. At the point where extra-basinal processes are replaced by permanent intra-basinal processes which determine the functioning and development of the wetland, dune slacks have evolved into a separate wetland type.

An expanded view and proposed division of dune slacks

Drawing upon the early literature and the case studies provided, there seems to be several settings, in terms of landform, stratigraphy, and hydrology, in which dune slacks can form, and a multiplicity of dune slack types.

As dune slacks are hollows within a coastal dune terrain, the term has been incorrectly applied to hollows within beach terrains, such as those developed behind spits, ephemeral tidal hollows behind beach cusps or storm berms, or hollows formed during tombolo development as a result of construction by refracted wave trains. Spits, developed at the apex of a cuspate foreland or along scalloped beach coasts, create shallow leeward depressions which, with subsequent development of foredunes and beach ridges superimposed on the spit or barrier, and on the stranded plain behind the spit, superficially appear as dune slacks. However, the initial development of the hollow was independent of a dune terrain and therefore requires a separate category of slack. In many cases these features may repeatedly form and be destroyed before conditions become suitable for their preservation.

A second example of a hollow unrelated to dune terrain but sometimes confused with dune slacks are barred marine embayments. Marine embayments can be very deep and are unlikely to be seasonal or freshwater for a long period (even when fully cut off from the sea). They are better categorised as a separate class of wetland.

Although dune slacks are coastal landscape features, coastal dune terrains may not always be linked to marine settings. There are examples of coastal dunes bordering estuaries, large lakes, and "inland seas", and these dune environments may comprise Holocene ephemeral or persistent slacks within a dune, beach ridge, or chaot terrain, seasonally inundated by water table rise, and underlain by Holocene sand derived from nearshore and onshore materials from the estuary, large lake, or the "inland sea". In appearance and function, these dune slacks are indistinguishable from dune slacks bordering marine environments.

In all coastal dune terrains, hollows may be formed in the following ways (Figure 3):

1. dune slacks situated wholly in Holocene coastal dunes, composed of Holocene sands, and subject to Holocene coastal processes (Figures 3A, B, C);

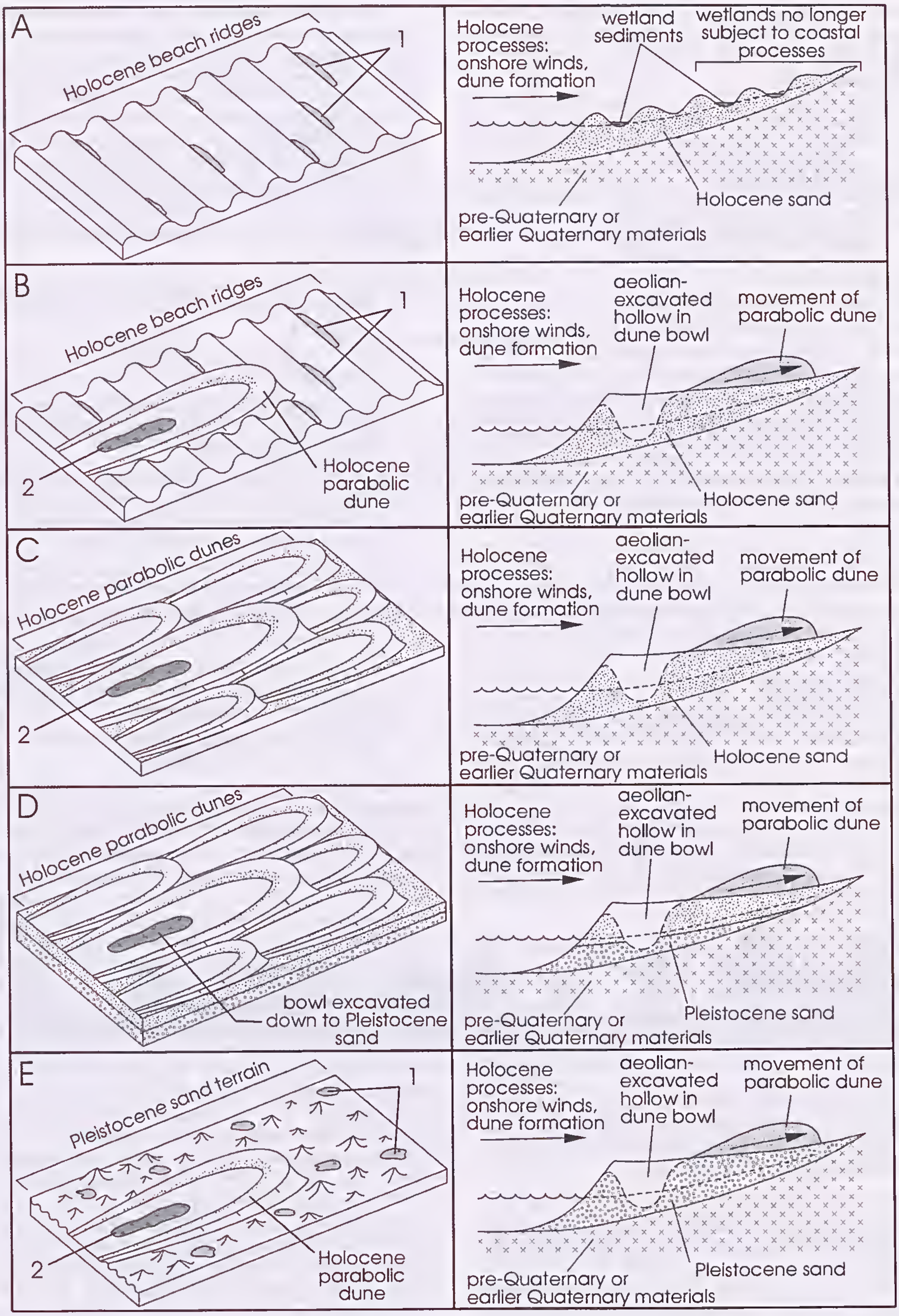


Figure 3. The various landscape and stratigraphic settings for the development of dune slacks, from wholly Holocene sands and Holocene dunes to Pleistocene sands reworked to form Holocene dunes. In all situations, the excavation by aeolian erosion intersects the water table or the zone of capillary rise.

2. dune slacks situated in Holocene coastal dunes, composed of Holocene sands, subject to Holocene coastal processes, on a Pleistocene sand basement (Figure 3D);
3. dune slacks situated in a coastal terrain of Holocene dune landforms, composed of Pleistocene or older sands reworked by Holocene coastal processes (Figure 3E);
4. dune slacks situated wholly in Holocene coastal dunes, such as beach ridge systems, or as chaots, composed of Holocene sands, but no longer subject to Holocene coastal processes (Figures 3A, B – far right).

The idea that dune slacks are wholly Holocene features, as described in Category 1, seems, from the literature, largely to have been assumed, or based on extant processes, rather than investigated radiometrically. It can be seen from this list that subscribing to the above conclusion of dune slacks as wholly Holocene features, in practice, is sometimes difficult to verify. Wetlands in coastal dunes that formed during the Pleistocene, but still function as coastal wetlands today, in a Pleistocene dune terrain,. underlain by Pleistocene unconsolidated or cemented basement materials, do not conform to the concept of dune slack, and may be excluded, but there are many examples of coastal dune settings which are more complex. The age of the dune slack becomes blurred where any one of the following conditions are present: 1) there is reworking and mixing of older and more modern sediments, 2) there are ongoing cycles of alternating erosion and deposition of dunes and beach ridges, 3) Pleistocene sediments become exposed to modern coastal processes as a result of coastal erosion and exposure at the coastline and 4) wetland stratigraphic layers derive from both Pleistocene and Holocene coastal processes and diagenesis. Unconsolidated coastal dunes formerly of Pleistocene origin, once again fronting a newly eroding coastline and becoming subject to coastal processes, or reworking of Pleistocene dunes or a Pleistocene pavement, by Holocene coastal processes, provide unconsolidated materials suitable for the current formation of dune slacks.

As a result of the above discussion, it is suggested that Categories 2 and 3 be included as dune slacks. Category 4 is excluded from dune slacks.

Wetlands situated wholly in Holocene coastal dunes, composed of Holocene sands, but no longer subject to Holocene coastal processes are more difficult to ascribe to the original definition and meaning of dune slacks. There exists a boundary which separates incipient and early stage dune slacks from older dune slacks which have become more permanent wetlands, and developed additional mechanisms to sustain them.

Dune slacks, separated geographically from the coast by ongoing progradation, become wetland components of a different setting, *i.e.*, an inland setting where the effects of wind are much less, where the water table configuration and contours flatten, and groundwater movement is slowed, creating a context for local, rather than regional, water flows. The older Holocene slacks described by C A Semeniuk (2007) and the older slacks in Donana National Park exemplify this situation and should be excluded as dune slacks.

Similarly, basins formed within a system of ingressing transgressive dunes, removed from the coast, are no longer coastal dunes and hence no longer subject to coastal processes. Transgressive dunes often move over rock outcrops or surfaces which are related to far older materials (*e.g.*, Precambrian rock basements) and whose aquifers have different hydrological recharge, storage, and discharge mechanisms. Wetland hollows in such settings are also excluded from dune slacks.

There are several hydrologic settings in which groundwaters seasonally recharge coastal dune wetlands (Figures 4 and 5):

1. a seasonally fluctuating water table under a simple prograded beach ridge plain or dune field (Figures 4A and 5);
2. local mounding of the water table under dune topography (Figure 5);
3. local mounding of groundwater behind coastal dunes caused by the barring of a stream, normal to the barrier (Figure 4B);
4. local mounding of groundwater behind coastal dunes that impede the regional groundwater flow, resulting in discharge at the base of the dunes at their seaward edge (Figures 4C, D);
5. groundwater perched on a Holocene impermeable surface underlying the coastal dunes (Figure 5);
6. surface water perched on a Holocene impermeable surface underlying the coastal dunes;
7. surface water and/or groundwater perched on a Pleistocene or older impermeable surface underlying the coastal dunes; and
8. perching on an impermeable layer formed intra-basinally by wetland processes.

The hydrologic situations listed above can be amalgamated into three broad groups: 1) unconfined seasonal groundwater fluctuation which causes the water table to intersect the ground surface, 2) seasonal groundwater mounding, and 3) seasonal perching of rain water or shallow groundwater. The traditional view of dune slack hydrology is that of the rising and falling of the regional water table due to its seasonal recharge by rainfall. However, localised water tables can be elevated above the regional water table through local mounding. Groundwater mounding may have the effect of inundating or waterlogging dune hollows which otherwise would be above the level of the regional water table. Categories 2–5 satisfy the classical view of water table rise. Perching or channelling of rain or groundwater, along a Holocene or older impermeable surface underlying the coastal dunes (categories 6, 7), is not comparable to raising the water table by local mounding. In some situations the bowl of the dune is excavated to a water table above the perching layer that is still within the dune terrain and its stratigraphy. In other situations, the bowl of the dune may intersect the underlying pavement or surface of a much older geological formation and, as such, exposes water directly perched on the hardpan. In the former situation the dune slack hydrology is equivalent to Category 2. In the latter situation, wind may expose the water that is directly on the hardpan or perching layer in the dune bowl, but during dry periods it cannot excavate any deeper, showing that the hard

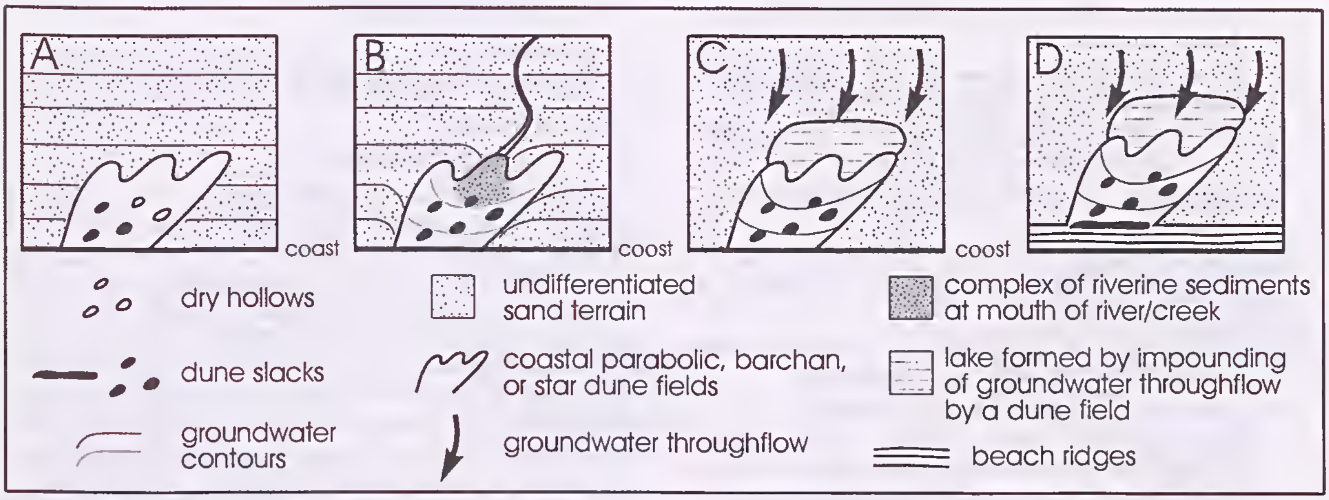


Figure 4. Idealised diagram showing dune fields ingressing inland with variable development of dune slacks. A. Simple dune field in a terrain with seaward sloping water table. B. Dune field in the path of a creek or river that has mounded the groundwater under the dunes so that the aeolian excavations intersect an "elevated" water table. C. Dune field in the path of a major zone of groundwater discharge, impounding the groundwater flow, creating a lake, and causing groundwater to mound under the dunes, so that the aeolian excavations intersect an "elevated" water table. D. Dune field in the path of a major zone of groundwater discharge, impounding the groundwater flow, creating a lake, and causing groundwater to mound under the dunes, so that the aeolian excavations intersect an "elevated" water table, and the elevated groundwater discharge at the interface, between the erosional dune field and the prograded beach ridges, creates a linear dune slack.

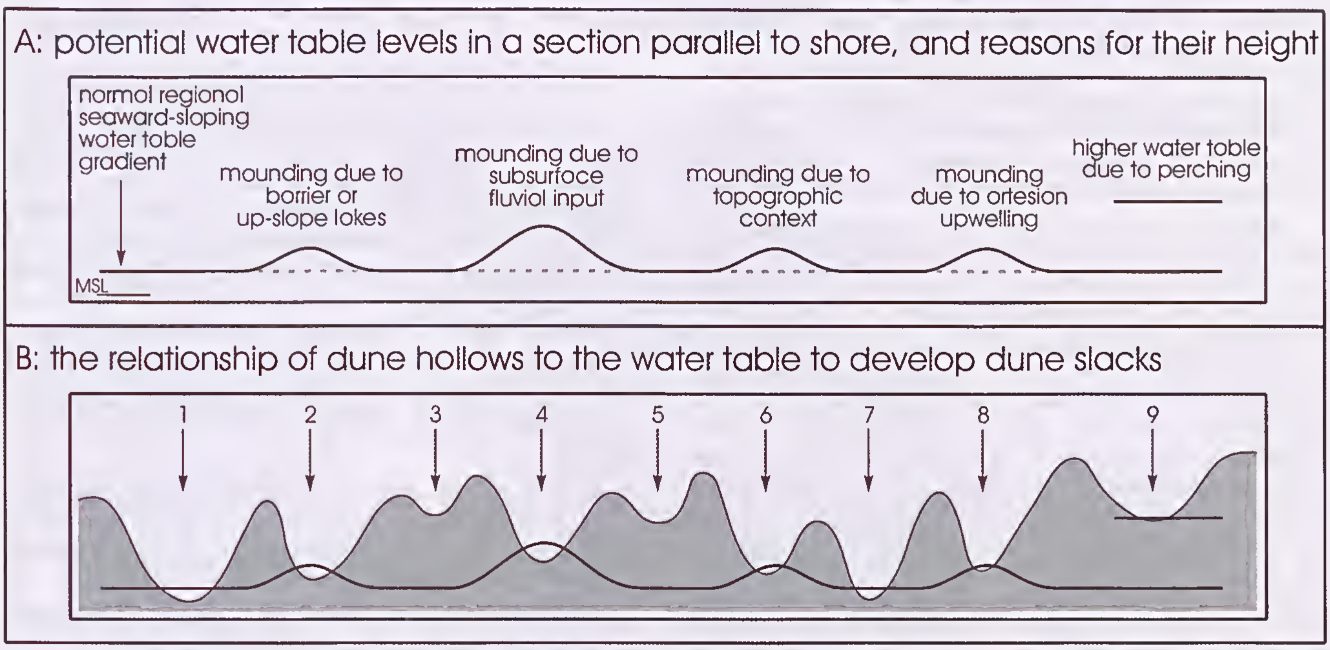


Figure 5. The settings for dune slacks hydrologically and geomorphologically. A. Possible levels of the water table under coastal dunes due to six different hydrological situations. B. Dune landscape superimposed on the water table configurations of (A) with varying intersection of the dune landsurface by the water table: 1 and 7 – dune bowl intersects the regionally seaward-sloping water table; 2, 4, 6 and 8 – dune bowls intersect various types of mounded water table; 3 and 5 – dune bowl does not intersect the water table; 4 – dune bowl intersects another type of mounded water table; 9 – dune bowl intersects a perched water table.

layer is not part of the dune dynamics. Categories 6 and 7 thus do not satisfy hydrological criteria for dune slacks. The situation, however, becomes more complex when it is the dune slack itself which generates a hardpan layer which retards vertical groundwater movement. The process described in Category 8 indicates that the wetland has now developed intra-basinal features which alter the basin hydrology to the extent that it is no longer a dune slack.

If the cut-off points discussed above are accepted, then the following description of dune slacks may provide a clearer meaning and scope for the term. The conclusions of this review and discussion are that:

1. dune slacks are wet hollows formed in coastal dunes and not inland dunes;
2. dune slacks differ from other coastal dune wetlands (such as dune-impounded fluvial

systems) in that they are formed by Holocene coastal processes;
3. dune slacks can form in an erosional or depositional dune or beach ridge setting;
4. dune slacks are subject to regional geomorphic, hydrologic and sedimentary processes;
5. dune slacks are subject to seasonal inundation or seasonal waterlogging;
6. dune slacks are maintained hydrologically by rainfall and groundwater and not by marine or fluvial processes;
7. dune slacks include the full range of water salinities from freshwater to hypersaline;
8. dune slacks can evolve from beach slacks;
9. dune slacks can evolve to other coastal wetland types (at Donana National Park in Spain, and the Becher Cuspate Foreland in Western Australia);
10. diagenetic alteration of sediments is one of the primary ways that dune slacks can evolve; and
11. geochemical changes or increase in nutrient content alone should not constitute criteria to change classification from dune slack to coastal wetland.

Some form of amended classification may be useful in separating and organising the different types of wetlands currently recognised in the category of dune slacks. Recognition of the variety of settings, geomorphic and hydrologic processes, and internal sedimentary, hydrochemical and geochemical interactions, occurring within dune slacks, has expanded the numbers and types of wetlands in this class. For purposes of conserving the full range of types, a simple subdivision is proposed here.

There are four coastal dune settings where dune slacks may form: marine, estuarine, large lakes, and "inland seas". Within these settings, there are two subdivisions of dune slacks: alpha types (α), formed in a depositional setting behind foredunes and beach ridges, and beta types (β), formed in an erosional setting between the arms of parabolic or star dunes, in the inter-dune depressions of a barchan dune field, and in and around conical dune residuals (the prefixes α and β are proposed in this paper to distinguish the two types). For β dune slacks, in Western Australia, wind erosion is most effective on dry sand during summer, when excavation may continue to the summer low water table level. With winter rainfall recharge, water tables rise above, or saturate the basin floor, to produce seasonally inundated or waterlogged basins, respectively. Descriptors used in other wetland classifications can also be used to further subdivide dune slacks, *e.g.*, saline, calcareous, acid, organic rich, or vegetated.

The regional factors in Western Australia important for development of dune slacks

In Western Australia, the regional factors important in the initial development of dune slacks and in their evolutionary pathways are:

1. geological/stratigraphic setting
2. Quaternary coastal setting
3. sand supply
4. coastal wind regime
5. climate
6. coastal sand composition
7. hydrology
8. biogeographic setting

The geological/stratigraphic setting of the coast is a critical factor in determining whether coastal dune fields, and hence dune slacks, develop. Geological setting, such as a tectonically active region where uplift exposes rocks to form extensive cliff shores, or where ancient bedrock is exposed, will determine coastal form and preclude slack development (Semeniuk *et al.* 1982; Semeniuk 2008; Brocx & Semeniuk 2011). For example, dune fields (and dune slacks) are not developed along the cliff shores of the Kimberley Coast, the rocky shoes of the western Dampier Peninsula, the rocky shores of the Dampier Archipelago, the rocky coastal tract between Cape Range and Cape Quobba, the limestone rocky shores between Dirk Hartog Island, Zuytdorp Cliffs to north Kalbarri region, the cliffed red sand terrain of Peron Peninsula (Shark Bay), the sandstone rocky shores of the Kalbarri region, the coast of the Leeuwin Ridge, and the limestone cliffs bordering the Nullarbor Plain (Figure 6). The sandy shore of the coastal Perth Basin has numerous coastal dune fields but, here, stratigraphy plays a role in whether there are dune slacks. The Quaternary coastal stratigraphy of the Perth Basin is generally Holocene sand (dunes) perched on or encroaching upon Pleistocene limestone, so that the coast comprises either a limestone cliff, or a dune field perched on a limestone "plateau". Aeolian erosion in such dune fields excavates hollows down to the underlying limestone and not to a water table. Where there are cuspate forelands, there is scope for mobile dune fields *and* for development of dune slacks. The southern coast of Western Australia has massive dune fields and dune slacks because it consists of Precambrian rock headlands and intervening connective dune barriers.

Quaternary coastal setting also determines whether dune fields and dune slacks are developed. The main Quaternary coastal settings in Western Australia are (Figure 6):

- deltas and tidal flats of the Cambridge Gulf, Kimberley and King Sound regions (Semeniuk 1993; Brocx & Semeniuk 2010, 2011; Semeniuk 2011; Semeniuk & Brocx 2011);
- barrier dunes and barrier limestone and tidal flats of Canning Coast (Semeniuk 2008);
- deltas, limestone barrier coasts, beach/dunes shores and ria/archipelago coasts, and extensive tidal flats of the Pilbara Coast (Semeniuk 1996);
- the delta complexes of the Gascoyne Delta (Johnson 1982) and Wooramel Delta (Logan 1970);
- the tidal flats and prograded seagrass complexes of Shark Bay (Logan 1974);
- the beach ridge plains and cuspate forelands of the Rottnest Shelf Coast (Searle & Semeniuk 1985);
- the Scott Coastal Plain shore;
- the barrier dune complexes of the south coast (Brocx & Semeniuk 2010; Semeniuk *et al.* 2011); and
- the dune accumulations between Israelite Bay and Eucla on the south coast.

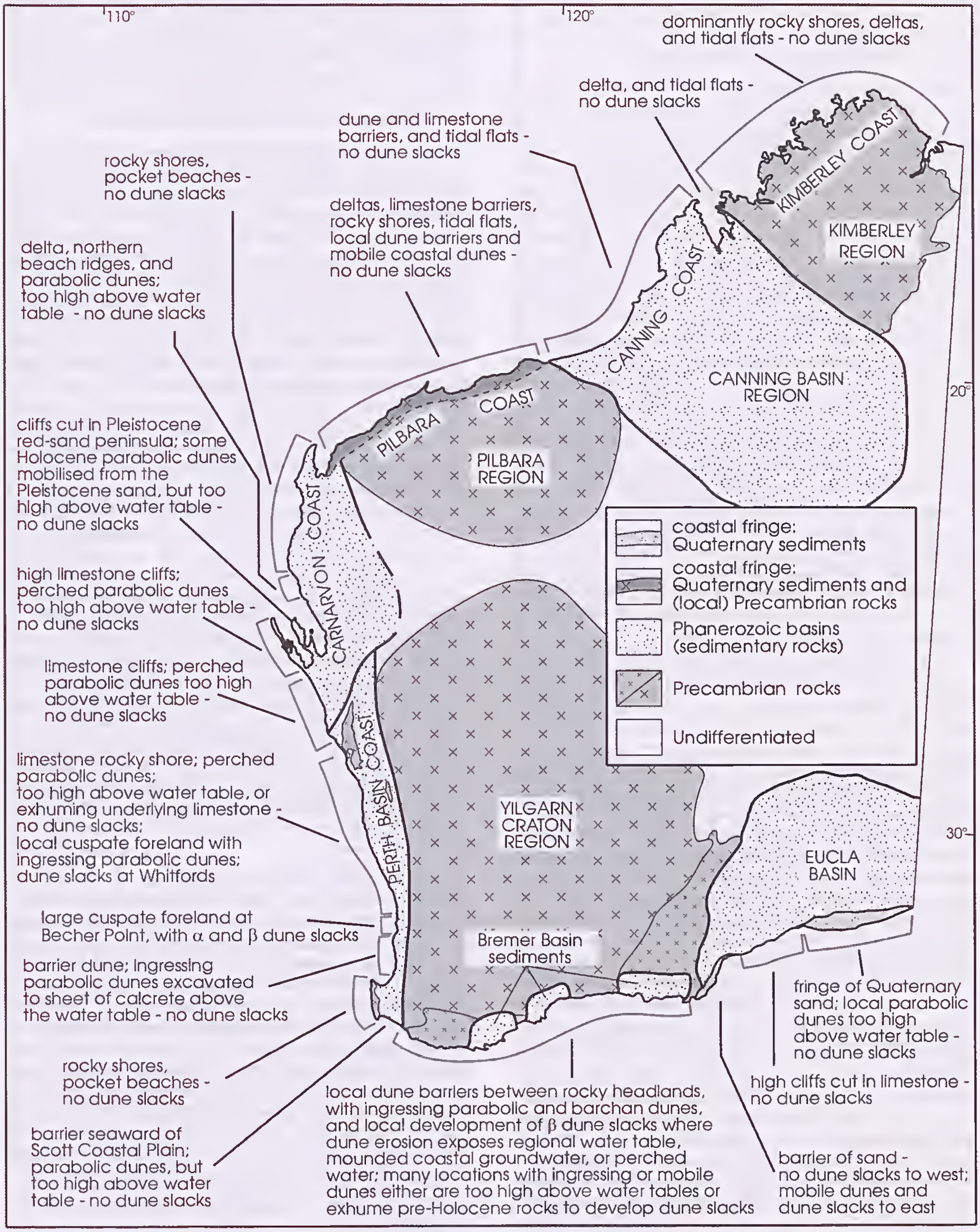


Figure 6. The Western Australia coast, showing its geological framework, the various sectors where different types of coasts are developed, the sectors where coastal dunes are developed, and where dune slacks are developed.

Tidal flats and deltas generally do not support massive coastal dunes and associated slacks. The main areas of Quaternary deposits where dune fields may develop are the beach ridge plains and cuspate forelands of the Rottnest Shelf Coast, and the coastal complexes of southern Western Australia (*cf.* Pye 1983).

Sand supply is critical to the development of coastal dune fields. Alongshore and onshore transport, erosion along the coast, and biogenic generation of sand in near-shore seagrass banks, supplies sediment to the shore (Searle & Semeniuk 1985, 1988; Searle *et al.* 1988; Semeniuk & Searle 1986). Massive dune fields, barrier dunes, and prograded beach ridges and dunes are developed in the following localities along coastal Western Australia: northern Dampier Peninsula, with reworking of Pleistocene sand into northerly shore transport (Semeniuk 2008); the dune barriers along the Canning Coast, with reworking of Pleistocene sand (Semeniuk 2008); Tubridgi Point (north-eastern Exmouth Gulf) with reworking of delta sand and red desert sand; the Bejaling Beach Ridges of the northern Gascoyne Delta (Johnson 1982); various cuspate forelands, beach ridge systems, and perched dunes along the coast of the Rottnest Shelf (Searle & Semeniuk 1985; Semeniuk *et al.* 1989), with reworking of Pleistocene quartz sand, erosion of Pleistocene limestone, biogenic generation from local seagrass banks, and alongshore transport from southern sectors (Searle & Semeniuk 1985); the coastal edge of the Scott Coastal Plain, with reworking of Pleistocene quartz sand; and the barrier dunes and perched dunes developed between and on rocky headlands of the south coast, with reworking and alongshore transport of Pleistocene quartz sand.

Once emplaced on the coast, sand is subject to the coastal wind regime and, depending on the wind's intensity, duration, direction, and season, it is mobilised into land-ingressing dune fields (Semeniuk *et al.* 1989). Sand mobility is most efficient in summer, when sea breezes intensify and sand is dry. The most intense winds in Western Australia in many locations are along coasts that are rocky shores, limestone shores and limestone terrains, and hence do not result in massive dune fields – the Pilbara Coast and the Shark Bay areas exemplify this. Strong winds, resulting in inland-ingressing dunes are located between Dongara and Bunbury on the west coast, and along the south coast. For the west coast, wind intensity increases northwards, and changes from westerly to south-westerly to southerly, and the dunes tend to be perched on Pleistocene limestone (as noted above). For the south coast, there are numerous ingressing dunes, with the majority perched on Precambrian rock, Tertiary plains, or Pleistocene limestone.

The coast of Western Australia, from north to south, has climates of Tropical humid, subhumid, semiarid, arid, and Subtropical arid, semiarid, subhumid, and humid. Along the south coast from west to east climate spans Subtropical/Temperate humid, subhumid, and semiarid. Mobile dune fields with dune slacks occur in climates of Subtropical subhumid, and Subtropical/Temperate humid, subhumid, and semiarid, with rainfall as low as 300 mm/pa and as high as 1400 mm/pa. In contrast, dune slacks in coastal United Kingdom and northern Europe are located in a Temperate oceanic climate (Trewartha 1968) with rainfall *circa* 750 to 1000 mm/pa – as such, they are situated in a relatively consistent maritime climate and biogeographic setting, and broadly have responded similarly in terms of landforms, soil development, geochemistry/hydrochemistry, and ecologic succession. Thus there is a wider range of climate zones for dune slacks in Western Australia, which have effects on vegetation biogeography and biodiversity, development of wetland sediments and soils, and diagenesis.

Spanning a large latitudinal range, and crossing a number of geological regions, coastal sands in Western Australia show a range in composition, from carbonate-dominated to quartz-dominated, and variably feldspar-bearing (Searle & Semeniuk 1988; Semeniuk *et al.* 1989), with variation reflecting local provenance such as seagrass banks, erosion of onshore materials, riverine input, or alongshore transport. In local areas, there also may be a strong component of opaque and heavy minerals, such as rutile, ilmenite, tourmaline, apatite, magnetite, amongst others (Baxter 1977). In the United Kingdom and northern Europe, initially carbonate-bearing dune slacks, with acid groundwater, undergo dissolution of carbonate, geochemically evolving from quartz-and-carbonate sand to quartz-rich sand, reflecting levels of "geochemical maturity" or "pedogenic maturity". This has been an important part of their dune slack evolutionary processes, with major effects on vegetation. However, in Western Australia, the compositional variation of coastal sands is such that the parent sands may be quartz, a calcareous/quartzose mix, calcareous, or containing opaque and heavy minerals. Some of these parent sands are at a compositional level that would be considered as "mature carbonate-depleted sand" in the United Kingdom and northern European dune slacks. Further, with the opaque minerals and feldspar in the sands of coastal Western Australia, there is a degree of geochemical diversity, in the inherent content of Fe, P and other elements, not recorded as present in dune slacks of the United Kingdom and northern Europe. In this context, dune slacks of Western Australia need to be described in terms of evolutionary pathways and geochemical pathways as systems distinct from existing models overseas.

Hydrological conditions required for dune slack development are seasonal rainfall and groundwater rise. On the western and southern coasts, winter rainfall recharges the groundwater in unconfined sandy aquifers and, as such, groundwater is fresh. Along the western coast, groundwater resides in calcareous sand, calcareous and quartz sand, or quartz sand and is carbonate enriched. On the southern coast, groundwater resides in mainly quartzose sand, and is carbonate-depauperate. The water table on which dune slacks are developed may underlie dune terrains in a number of configurations (Figure 5), *viz.*, a seaward sloping unconfined ground water table as part of the regional gradient; locally mounded groundwater; and perched groundwater (though not perched directly on rock or a hardpan).

Biogeographic setting is also an important factor in the evolution of dune slacks. In Western Australia, the coastal systems with dune slacks cross several biogeographic zones (Hopper 1979; Thackway & Cresswell 1995; Myers *et al.* 2000; Hopper & Goia 2004). The dune slack plants and other biota, that evolve from simple to more complex

systems, are specific to the biogeographic setting. Dune slacks in semiarid/arid regions may support fewer species of rushes and sedges, whereas those in humid regions initially support a higher diversity of rushes and sedges and quickly give way to complex vegetation associations.

Dune slacks in Western Australia

In Western Australia, dune slacks have been identified in six regions. From north to south, they are: Whitfords and the Rockingham-Point Becher area on the west coast, and Meerup chaots and Yeagarup barrier dune, Reef Beach area (south of Moates Lake, east Albany, Warramurrup dune field (near Bremer Bay), and Bilbunya, east of Israelite Bay on the south coast (Figure 7). A description of the dune slacks follows. Data on rainfall, dune sand grainsize, dune slack grainsize and sediment type, and water salinity and pH for the various dune slacks are presented below. Maps of the dune slacks, aerial photographs, and wind rosettes for various sites are shown in Figures 8–13. Details of substrate geochemistry/mineralogy, the opaque/heavy mineral component of the dune sands and dune slacks (variable along the coast, both regionally and locally), and the hydrochemical and pedogenic evolution of dune slacks are beyond the scope of this paper and will be presented in a later study.

Whitfords

The dune slack at Whitfords is a seasonally waterlogged basin located on a Holocene cuspate foreland (Semeniuk & Searle 1986) in a subtropical subhumid climate with rainfall of ~ 870 mm per annum. It is a β dune slack in a swale behind the foredune. Sand surrounding the dune slack is fine to medium gained quartz-calcareous (40–60% $CaCO_3$). The slack is underlain by a thin layer (< 1 cm) of calcilutite. Dune slack water has salinity of 900 ppm, a pH of 7.3–7.9, and is oligotrophic. The dune slack was vegetated by low coastal heath and *Lepidospermum gladiatum* sedge.

Point Becher area

The dune slacks of the Point Becher area are located on a cuspate foreland (Figure 8) in a subtropical subhumid climate with rainfall of 822 mm per annum. Several types are present: α dune slacks situated in swales of beach ridges at the western and youngest part of Point Becher; barred marine lagoons evolved to become freshwater dune slacks; and β dune slacks in the bowls of parabolic dunes and chaots (C A Semeniuk 2007). They have all been subject to water table rise following coastal progradation and stranding and are freshwater systems (C A Semeniuk 2007). Dune sand in the region has 30–40% $CaCO_3$, and is fine to medium grained. Dune slack water has salinity of 50–400 ppm, a pH of 7.1–8.3, and is oligotrophic.

Dune slacks in the swales between beachridges exhibit groundwater throughflow and experience coastal processes. The youngest dune slack is seasonally waterlogged, and underlain by calcareous sand, humic sand, and calcilutaceous muddy sand. Slightly older slacks are seasonally inundated, and underlain by thin calcilutite (10–20 cm) and calcilutaceous muddy sand. They are vegetated mainly by sedges *Baumea juncea*,

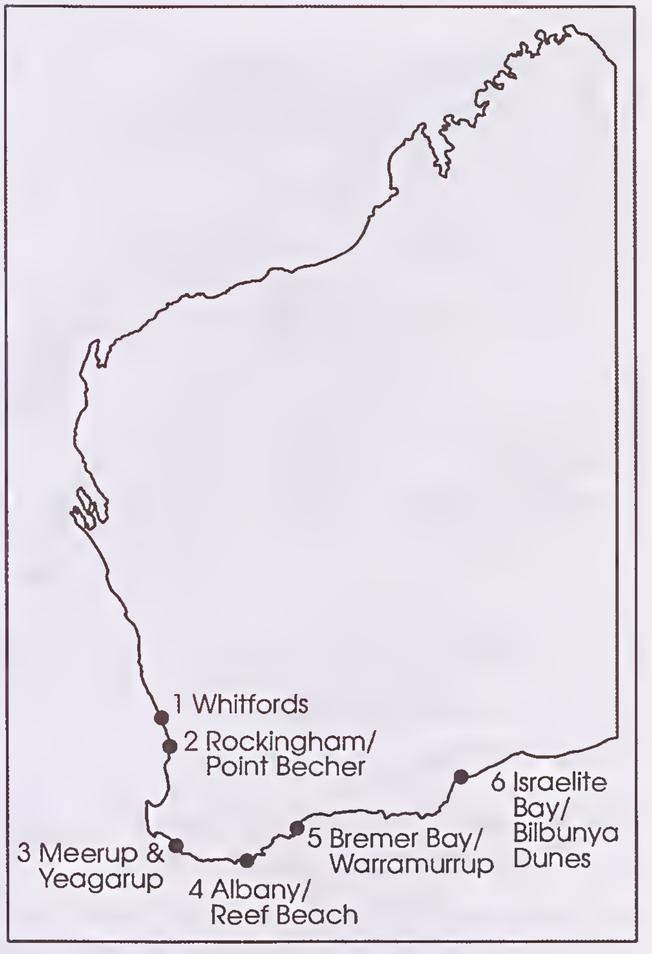


Figure 7. Location of dune slacks in Western Australia

Lepidospermum gladiatum, and *Ficinia nodosa*, and older slacks exhibit herbs *Centella asiatica* and *Lobelia alata*.

The former barred lagoons still retain evidence of spit development within their basins. They are seasonally inundated, underlain by thin calcilutite (10 cm) and organic-matter-enriched calcareous sand, and vegetated by rushes *Juncus kraussii*, herbs *Samolus repens*, and scattered low coastal shrubs *Halosarcia halocnemoides*. Hydrology and hydrochemistry now are mainly freshwater, but the seaward barrier to the most seaward wetland is intermittently breached and the wetland, for a short time, becomes brackish.

At Secret Harbour, β dune slacks are in the deflated bowls of northeasterly oriented parabolic dunes within an erosional setting of mobile sand sheets and conical dune residuals (Figure 9). The slacks are seasonally waterlogged and seasonally inundated basins, oval to linear in shape, and underlain by freshwater. They are underlain by richly calcareous quartzose sand, humic sand, and calcilutaceous muddy sand. Some slacks are bare, due to the rapidity of infilling and excavation, but others are colonised by herbs, patches of the rush *Juncus kraussii* and various coastal heaths.

Meerup chaots and Yeagarup barrier dune

On the south coast between the Warren and Meerup estuaries, and along the coastal zone eastwards of the

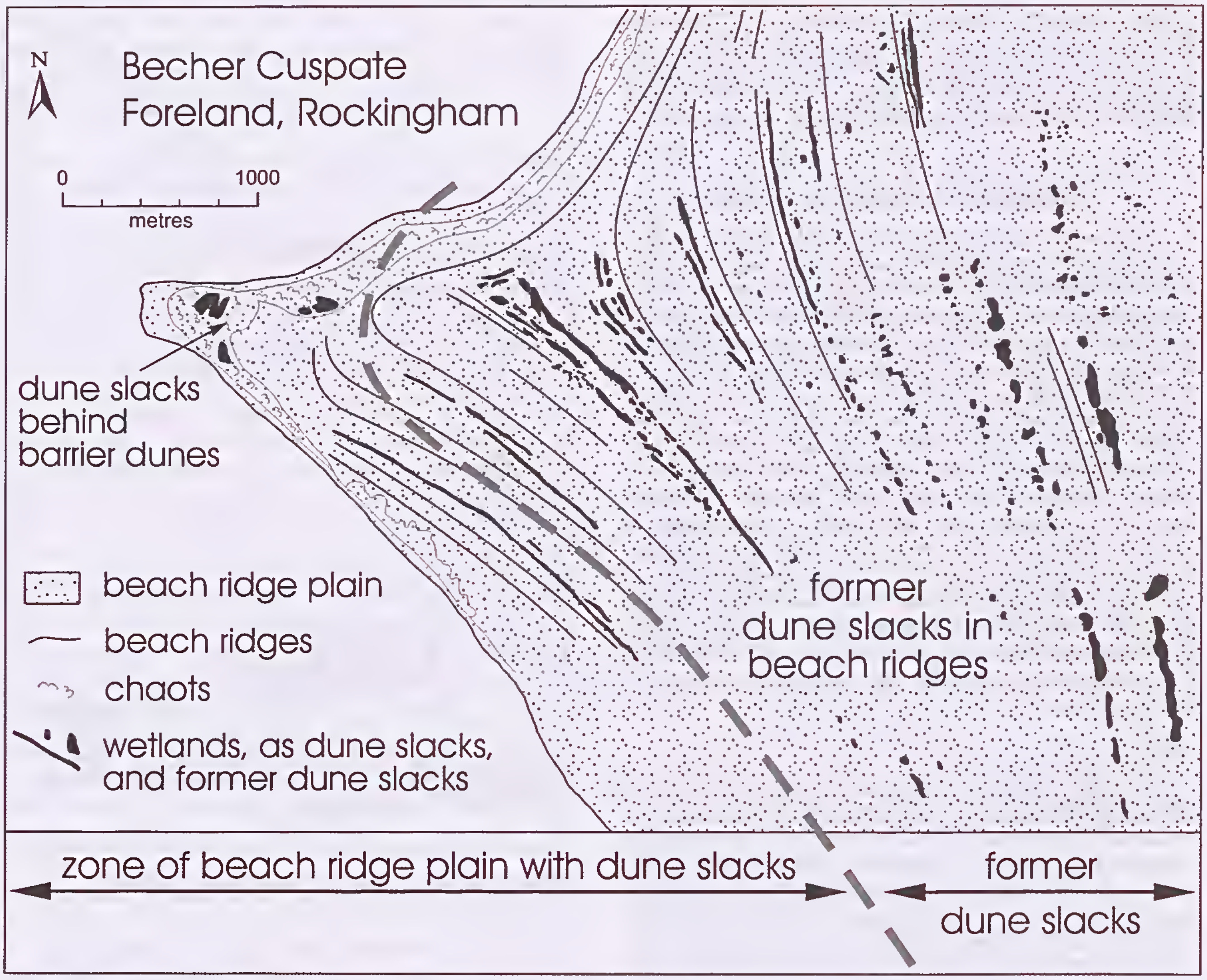


Figure 8. The Becher Point Cuspate Foreland, showing location of α dune slacks in the western and south-western part of the cuspate foreland, and the occurrence of the former α dune slacks in the eastern part of the cuspate foreland.

Warren estuary, in a climate setting of subtropical humid with an annual rainfall of 1400 mm, successive foredunes and aeolian erosion have produced an irregular series of swales, with shore parallel hummocky ridges, depressions, and incipient blowouts (essentially a terrain of chaots), which host numerous microscale to leptoscale, and sometimes ephemeral, seasonally inundated and waterlogged β dune slacks (Figure 10). Dune sand in the chaots has 2.5–5.0% $CaCO_3$, and is medium grained. Dune slack water has salinity of 514–675 ppm, a pH of 7.4–8.1, and is oligotrophic. The sedimentary fill of the dune slacks is calcareous/quartzose organic matter enriched sand, and they are vegetated by *Baumea juncea* sedge and *Centella asiatica* herbs.

Landward of the chaot terrain, Holocene parabolic dunes have mounted the onshore limestone ridges creating the massive Yeagarup dune fields, separated from the shoreline, but still subject to coastal aeolian processes, and there are β dune slacks in the bowls (Figure 10). Dune sand in the barrier has 0.5–6.0% $CaCO_3$, and is fine to medium grained. The dune slacks are seasonally waterlogged and seasonally inundated basins, which intersect the groundwater that resides in the dune stratigraphy. Dune slack water has salinity of 34–400 ppm, a pH of 7.8–8.1, and is oligotrophic. They are generally vegetation-free, underlain by bioturbated sand.

Reef Beach dune slacks

Between Moates Lake and Reef Beach, east of Albany, with a climate of subtropical subhumid and annual rainfall of 930 mm, β dune slacks occur in an erosional setting of ingressing parabolic dunes. They are microscale to leptoscale, seasonally waterlogged, irregular basins in deflation hollows, underlain by quartzose sand, and unvegetated, due to their ephemeral nature in this dynamic setting (Figure 11). Dune sand has 12–14% $CaCO_3$, and is fine grained. Dune slack water has salinity of 500 ppm, pH of 7.3–7.9, and is oligotrophic.

Warramurrup dune field

Dune slacks at Warramurrup near Bremer Bay, with a climate of subtropical subhumid and annual rainfall of 600 mm, occur in an erosional setting with north east oriented barchan dunes at the back of the beach

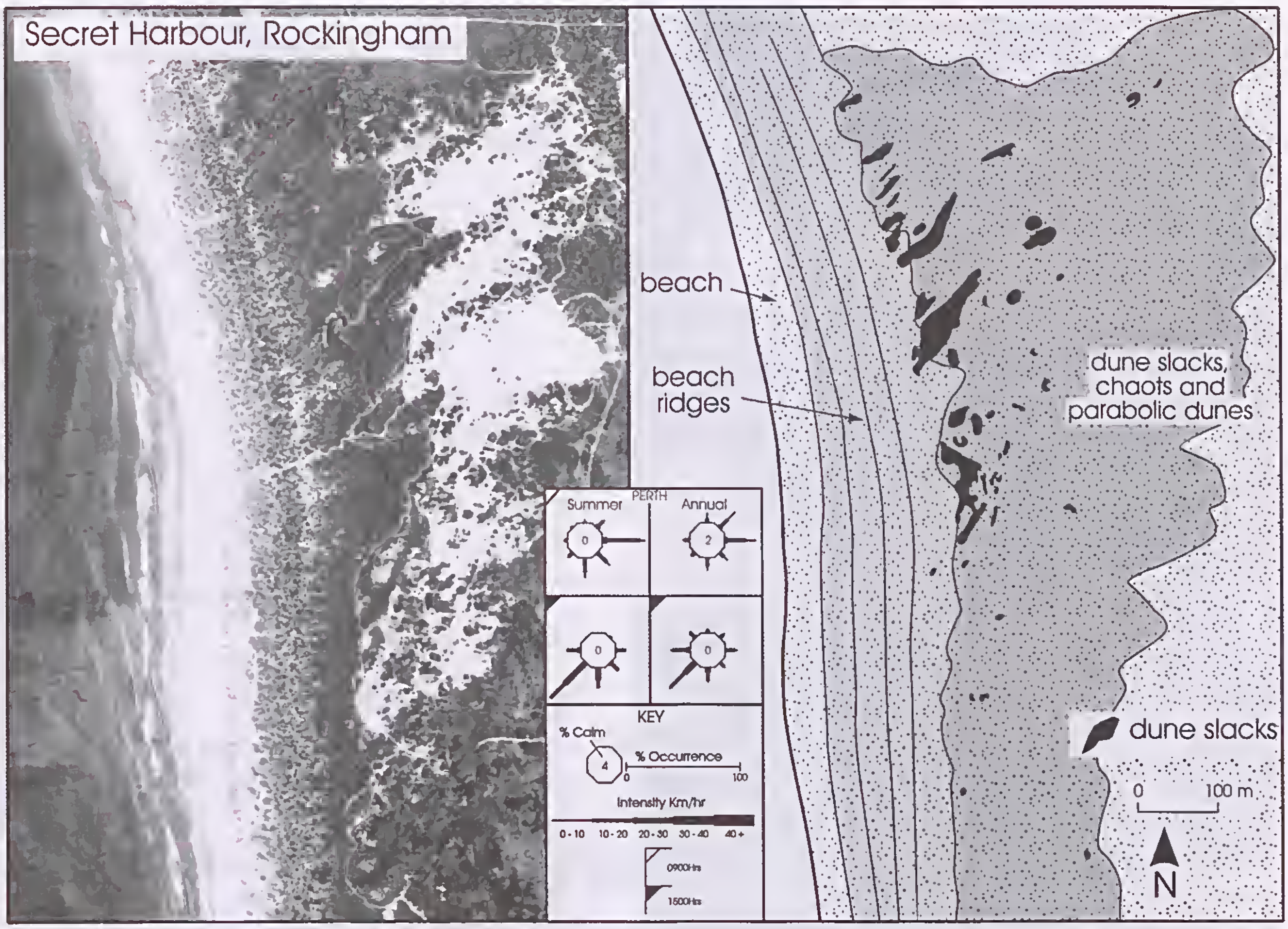


Figure 9. Aerial photography showing the erosional inland ingressing dune field of the Peelhurst Suite at Secret Harbour, and map of the β dune slacks developed in the direction of the prevailing onshore summer winds (see wind rosette inset). The zone of β dune slacks has been separated from the sea by progradation of beach ridges.

(Figure 12). They are microscale, seasonally inundated β dune slacks, which are underlain by quartz sand and are unvegetated. Dune sand has 14–28% $CaCO_3$, and is medium grained. Dune slack water has salinity of 160–800 ppm, a pH of 7.0–7.9, and is oligotrophic.

Bilbunya Dunes

The region of the Bilbunya Dunes, with a climate of subtropical semiarid and annual rainfall of ~270 mm, is a complex of β dune slacks (Figure 13). From Israelite Bay to the Bilbunya Dunes, the coast is a coastal plain with high sand dunes and elongated lagoons and the eastern part of the coastal plain is comprised of star dunes, barchan dunes, and chaots. The Holocene coastal dunes are underlain by fine quartz sand and bioclastic calcium carbonate grains, and sheet or nodular calcrete 30–60 cm below the surface (Lowry & Doepel 1974). Dune sand has 1–38% $CaCO_3$. Dune slack water has salinity of 40–750 ppm, a pH of 7.4–8.2, and is oligotrophic. The dune slacks form in three areas: between the arms of the star dunes as seasonally waterlogged and inundated basins, between the barchan dunes as seasonally waterlogged basins and palusplains, and between the chaots on the backshore of the beach as seasonally waterlogged and inundated basins. The sedimentary fill is composed of the same material as the dunes, but some evidence of diagenetic alteration (staining and cementation) is evident. Windswept moist palusplains may exhibit a surface of wind-adhesion ripples. Most slacks are bare, but some support herb vegetation.

Former dune slacks in Western Australia

Dune slacks of course evolve and, as noted earlier, if their surrounding terrain is stranded too far from the coast, coastal processes of dune mobility and dune re-activation cease, or intra-basinal wetland processes begin to dominate, such wetlands cease to be dune slacks, or be part of a dune slack environment (Figure 14). In Western Australia, wetlands that were former dune slacks, but have evolved beyond the dune slack stage, occur at Jurien, at Rockingham, on the western dune barrier to Lake Walyungup, Rockingham Plain, Warnbro shore, and Becher Point eastern wetlands, at Busselton, in beach ridge swales, at Prevelly, in dune chaot terrain, and at Albany, in beach ridge swales.

Jurien

Wetlands, that began as β dune slacks in the bowls of

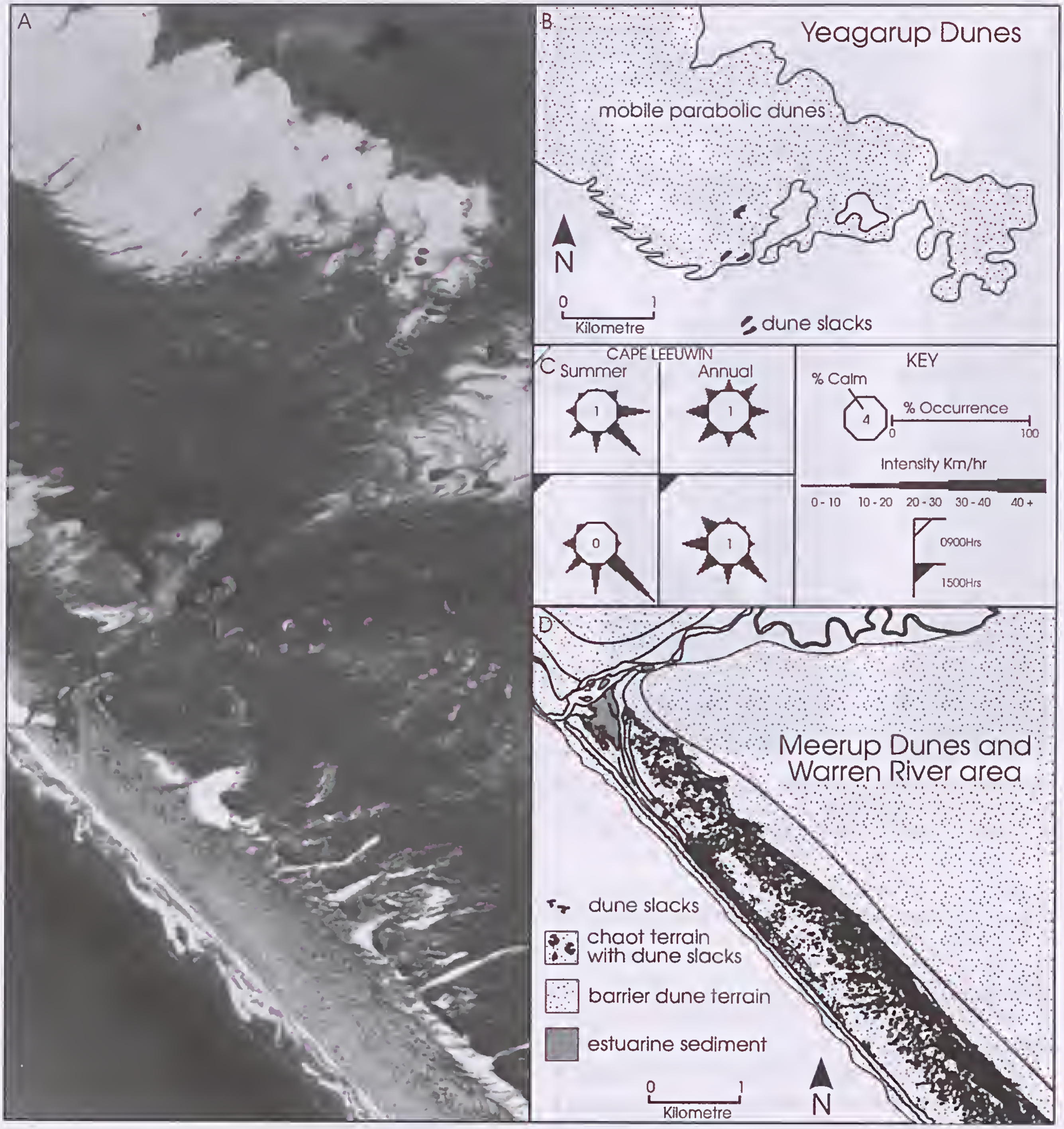


Figure 10. A. Aerial photography showing the Meerup-Yeagarup area. The inland Yeagarup dunes are a massive dune field perched on limestone. B. Location of β dune slacks in the inland Yeagarup dune field. C. Wind rosettes for the region from Cape Leeuwin data. D. The location of β dune slacks in the Meerup chaot dune terrain proximal to the coast.

NNE-trending attenuated parabolic dunes on Holocene sedimentary deposits, are now located in immobile (vegetated) dune terrain, and no longer in the dune slack environment. These wetlands exhibit one of three stratigraphic types: 1) seasonally waterlogged basins underlain by humic sand, depleted of carbonate grains, and vegetated by rushes and sedges, 2) seasonally waterlogged basins underlain by thin calcilutite (< 1 cm), vegetated by rushes, sedges, and low coastal heath, and 3) seasonally inundated basins underlain by thicker calcilutite (~ 10 cm), vegetated by coastal heath communities with interspersed sedges and herbs. The wetlands are waterlogged or inundated by seasonal fresh groundwater rise, and those, underlain by thicker calcilutite, also perch rainwater.

Peelhurst Suite western Lake Walyungup

Wetlands that began as β dune slacks in bowls of SW-trending parabolic dunes on the barrier that isolated Lake Walyungup from the ocean are now in fixed (vegetated)

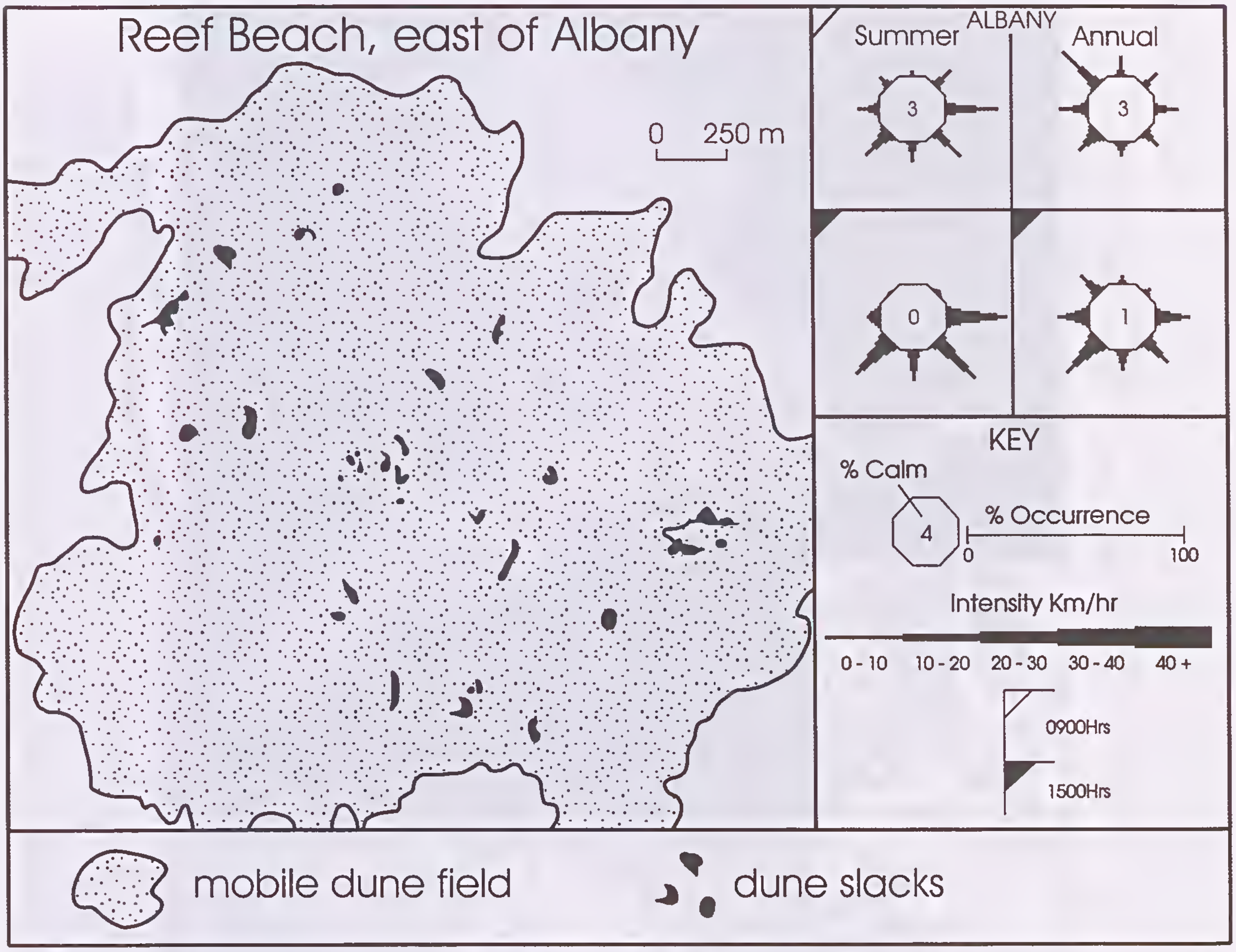


Figure 11. The Reef Beach Dune field east of Albany showing β dune slacks in the mobile dune system. Inset shows wind rosettes for the region from Albany data.

dunes, well inland from the coast. These wetlands are seasonally waterlogged and seasonally inundated basins, which are recharged by seasonal fresh groundwater rise, and perch rainwater. They are underlain by 10–20 cm of calcilutite, and vegetated by rushes, sedges, herbs, and low coastal heath.

Rockingham Plain

Swales of the beach ridge complex, some 6000–5000 years old, of the Rockingham Plain (Searle *et al.* 1988), began as α dune slacks and have developed to the stage that they have ~ 1 m of calcilutite, capped by indurated calcilutite. They are stranded inland, and no longer in the dune slack environment. They are seasonally waterlogged and seasonally inundated basins, vegetated by rushes, sedges, herbs, and low coastal heath. The wetlands are recharged by seasonal fresh groundwater rise, and also perch rainwater.

Warnbro shore

The northern shore of Warnbro Sound, the location of the former Peel Harbour (surveyed by John Septimus Roe in 1839, and re-surveyed by Commander Archdeacon in 1878) that rapidly infilled with coastal sediments during the period 1839 to 1878 was an area of beach slacks, underlain by calcareous quartzose sand.

Becher Point eastern wetlands

The central and eastern part of the Becher Point cuspate foreland, some 4500–1500 years old, has numerous linear, ovoid and circular swale wetlands in the beach ridge complex (C A Semeniuk 2007). They began as α dune slacks but are now stranded inland, and have accumulated 0.5–1.0 m of calcilutite. They are no longer in the dune slack environment. They comprise seasonally waterlogged and seasonally inundated basins, vegetated by rushes, sedges, herbs, low coastal heath, and paperbark trees. The wetlands are waterlogged or inundated by seasonal fresh groundwater rise, and also perch rainwater.

Beach ridge swales, Busselton

The southern central beach ridge complex at Busselton (Searle & Semeniuk 1985), 5000 years old, has linear swale wetlands (Semeniuk *et al.* 1989). They began as α dune slacks but now are stranded inland, and have accumulated up to 0.5 m of peat. They are no longer subject to coastal processes. They are vegetated by rushes,

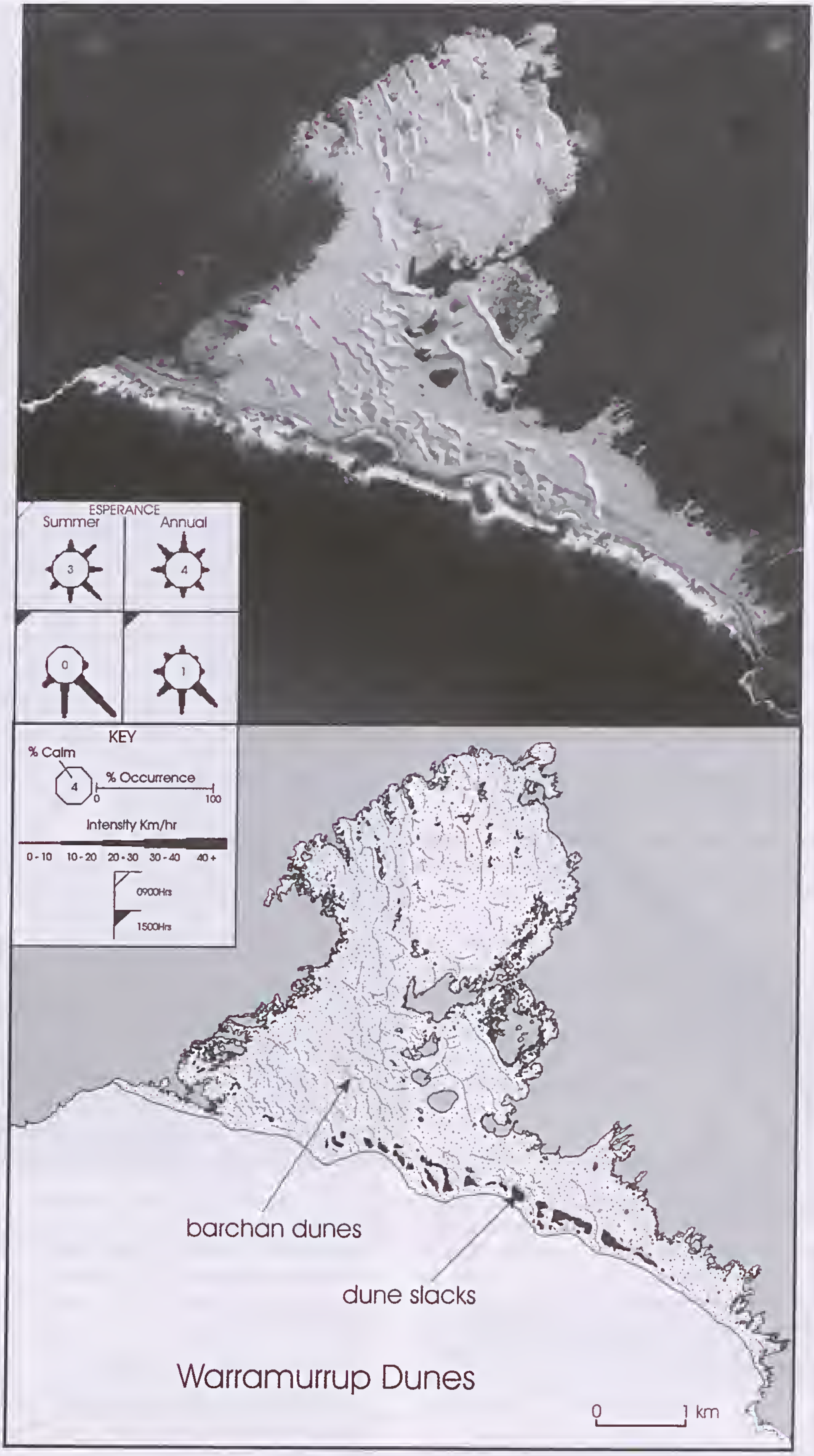


Figure 12. The Warramurrup Barchan Dune field. Aerial photograph shows the erosional inland ingressing dune field at Warramurrup, and the map shows location of β dune slacks in the mobile dune terrain proximal to the coast. Inset shows wind rosettes for the region from Esperance data.

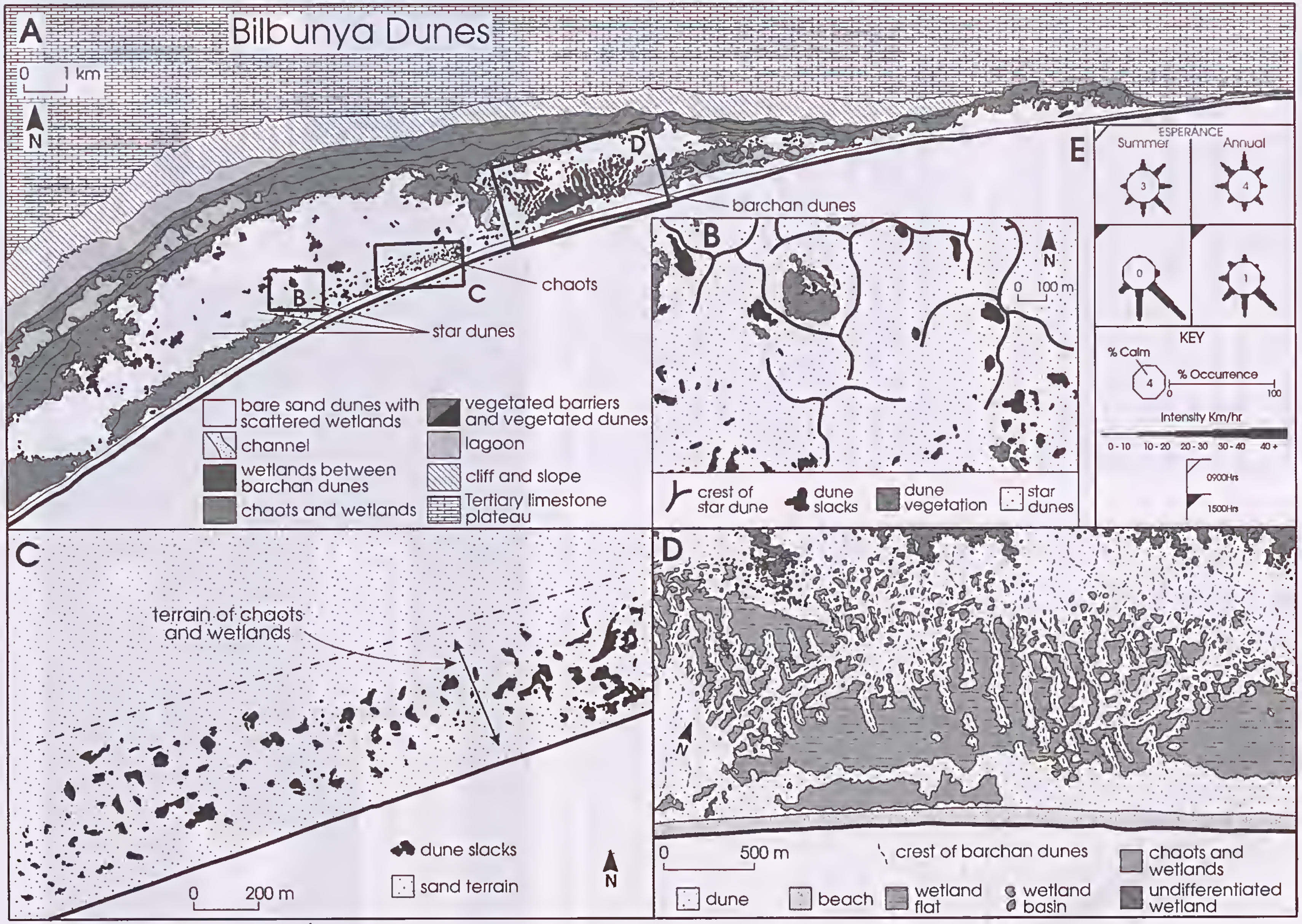


Figure 13. The Bilbunya Dune system. A. Overview of the Bilbunya Dunes showing location of the star dunes, the barchan dunes and the chaot dune terrain that are host to dune slacks. B. The star dune system with dune slacks in the star dune inter-arms. C. The chaot dune terrain with dune slacks in the hollows and depressions. D. The barchan dune system with dune slacks in the inter-dune flats and depressions. E. Wind rosettes for the region from Esperance data.

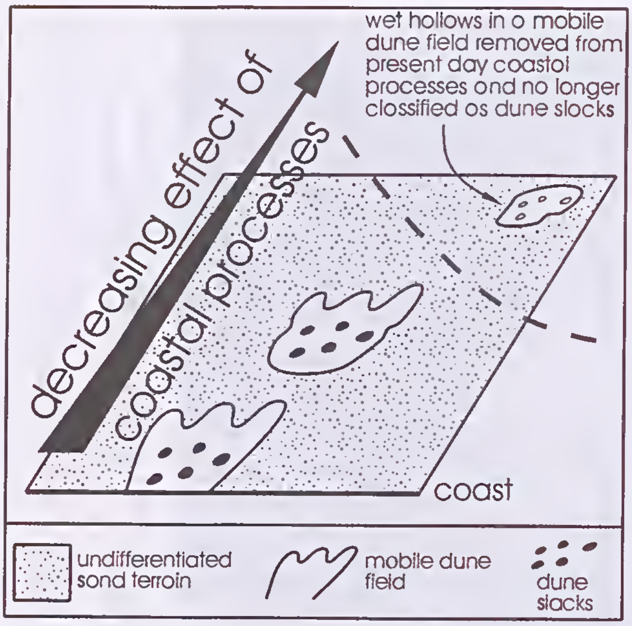


Figure 14. Idealised diagram showing the boundary between a dune system experiencing coastal processes and forming dune slacks, and an inland dune system and wetlands but no dune slacks owing to the decrease in the effect of coastal processes.

sedges, herbs, low coastal heath, and paperbark trees. The wetlands are waterlogged or inundated by seasonal fresh groundwater rise, and also perch rainwater.

Chaot dune terrain, Prevelly

Inland of the coast at Prevelly, there are former chaot dunes. The lowland and depressions of this terrain were formerly β dune slacks, but now are relict, and have accumulated up to 0.75 m of peat. They no longer function as dune slacks. They are vegetated by rushes, sedges, herbs, low coastal heath, and paperbark trees. The wetlands are waterlogged or inundated by seasonal fresh groundwater rise, and also perch rainwater.

Beach ridge swales, Albany

The Vancouver Peninsula (a tombolo), south Albany, comprises beach ridges and linear swale wetlands, waterlogged or inundated by seasonal fresh groundwater rise. The wetlands began as α dune slacks but are stranded from coastal processes, and have accumulated 0.5 m of peat. Younger former dune slacks are vegetated by sedges and paperbarks; older former dune slacks are vegetated by sedges, with peripheral low shrubland. The wetlands have developed to the stage that they are no longer in the dune slack environment, subject to coastal processes.

Where dune slacks are not developed and why

There are many locations along coastal Western Australia where there are mobile dunes, inland ingressing dune fields, or a major field of parabolic dunes, but without development of dune slacks. The areas are: northern Dampier Peninsula, Tubridgi Point, Bejaling Beach Ridges, Faure Island, Edel Land parabolic dunes, Jurien beach ridges, parabolic dune fields between Jurien Bay and Whitfords, parabolic dune fields of the Leschenault-Preston Barrier, parabolic dune fields between Bunbury to Busselton, parabolic dunes along the seaward Scott Coastal Plain, parabolic dunes along the coastal D'Entrecasteaux area, parabolic dunes of the Circus Beach Barrier, parabolic dunes of the Bellanger Barrier, parabolic dunes, west of Bremer Bay, parabolic dunes, west of Esperance, and parabolic dunes, east of Esperance. This section explores the reasons why dune

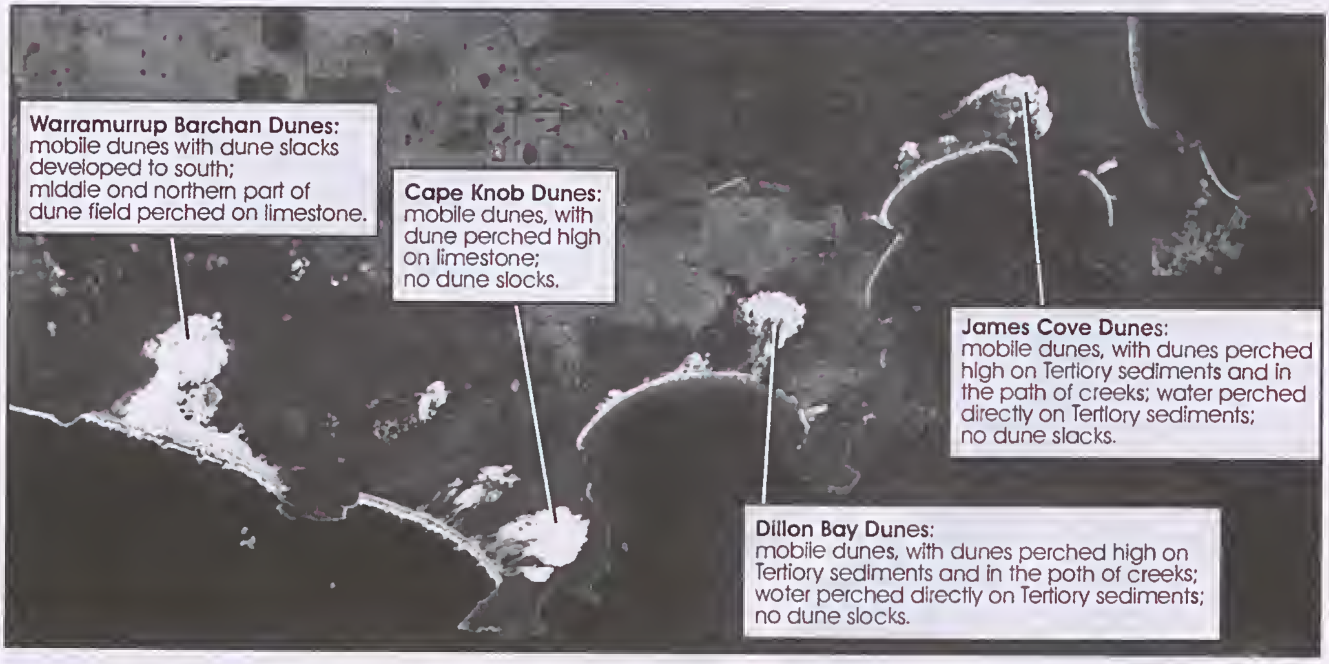


Figure 15. Aerial photograph of the Bremer Bay area showing four mobile inland ingressing dune fields but with dune slacks developed only on the Warramurrup barchan dune system. The other dunes are perched on limestone or on Tertiary sediments, and while for the Dillon Bay dunes and the James Cove dunes there are wetlands in the landward parts of the dune complex, these wetlands are directly perched on Tertiary sediments and directly recharged by surface fluvial flows.

slacks are not developed. Table 2 provides description of these areas in terms of coastal and stratigraphic setting, and sets out why dune slacks are not developed.

In most areas, one or more of the following reasons explain the lack of dune slack development: 1) lack of seasonally dominant onshore winds; 2) dunes and the wind-excavated dune bowls are too high above the water table; 3) there is an impedance to seasonal groundwater rise; 4) dunes are perched on Precambrian rock, Tertiary sediments of the Plantagenet Group, or on Pleistocene limestone, and excavation of the dune bowl exposes bedrock or limestone well above the water table, and 5) the dune bowls are tidally influenced, or are excavated to underlying tidal deposits.

Discussion

Using Western Australian coastal variability, and the basic tenet of 'what constitutes a dune slack', we have developed an expanded definition of dune slack geomorphology, hydrology, and hydrochemistry. Study of coastal geomorphology has resulted in identifying both Holocene erosional and depositional settings where coastal processes are still active in influencing dune slack formation and function. The notion of a dune slack has been broadened to encompass all coastal dune systems, whether they are marginal to marine systems, estuaries, large lakes, or "inland seas".

The main hydrological processes, associated with dune slacks, such as seasonality and water table rise, have been retained, but the means by which these take place have been expanded to include locally mounded and perched groundwater, as long as coastal dune processes interact with the groundwater systems to form wetlands.

Dune slack hydrochemistry derives from parent dune geochemistry, the wetland fills, and climate. Hence, coastal dune systems, in various stratigraphic contexts with different parent sand geochemistry and different climate regimes, exhibit different water salinities and hydrochemistry. Climate also affects plant biogeography and productivity, so that dune slacks along the Western Australian coast sustain varying plant assemblages and biodiversity. Vegetation contributes variable amounts of organic matter to wetland fills (from enrichening the wetland substrates in organic matter to the formation of peat), which can shift dune slack waters from alkaline to acid, and, for carbonate-bearing sands, change carbonate-rich substrates to carbonate-depleted substrates. Dune slacks and former dune slacks cross several plant biogeographic zones and major climate zones (Gentilli 1972; Hopper 1979; Beard 1980; Thackway & Cresswell 1995; Lyons *et al* 2000; *Myers et al 2000*; Hopper & Gioia 2004; *Environment Australia 2007*), and these provide an interesting framework within which to study the spatial variation in dune slacks, their biological diversity, and their evolution to coastal inland wetlands.

Compositional variability of sands along the extensive Western Australian coast necessitates adjusting notions of sand composition as the basis for dune slack maturity, since the sands range from carbonate-rich to quartz-rich without any implication that they represent stages in dune slack development. Based on overseas models and perceptions, some parent sands for dune slacks in Western Australia would be categorised into specific "maturity classes" before they have even begun pedogenically and diagenetically evolving. The locally developed opaque (and heavy) mineral suites of coastal sands of Western Australia add complexity to the understanding of pedogenic and diagenetic evolution of

Table 2

Locations where there are dune fields but no dune slacks

Location	Coastal and stratigraphic setting	Why dune slacks are not developed, or why wetlands are not dune slacks
northern Dampier Peninsula	dunes are reworked middle Holocene barriers (Semeniuk 2008) forming massive vegetation-free dune fields; dunes encroach landwards over tidal flat sediments	the aeolian excavations expose underlying tidal sediments, which perch rainwater; some of the dune bowls are in hydraulic contact with tidal creeks
Tubridgi Point	dunes are reworked delta deposits and desert sand (Semeniuk 1996) forming large vegetation-free dune fields; dunes encroach landwards over tidal flat sediment	aeolian excavations expose underlying tidal sediment which perches rainwater; some of the dune bowls are in hydraulic contact with tidal creeks
Bejaling Beach Ridges	northern part of Gascoyne Delta (Johnson 1982) that bars southern end of Lake McLeod	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks
Faure Island	local coastal erosion, and aeolian reworking and transport of Pleistocene Peron Sand (Logan 1970) forms modern ingressing parabolic dunes (Nilemah Sand; Logan 1970)	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks
Edel Land parabolic dunes	Pleistocene Tamala Limestone (Logan 1970) of mainly lithified parabolic dunes; local aeolian reworking of semi-lithified sand forms into modern ingressing parabolic dunes	Pleistocene lithified parabolic dunes, even if their bowls intersect the water table, are outside the scope of 'dune slack' environments as they are fixed and not Holocene features; the modern parabolic dunes and their bowl excavations are too high above water tables to form dune slacks

Table 2 (cont.)

Location	Coastal and stratigraphic setting	Why dune slacks are not developed, or why wetlands are not dune slacks
Jurien beach ridges parabolic dune fields, Jurien Bay to Whitfords	Holocene prograded beach ridge plain Holocene dune fields perched on Pleistocene limestone	swales do not intersect the water table bowls of parabolic dunes are excavated to basement limestone
parabolic dune fields, Leschenault-Preston Barrier	dune barrier with eastward migrating parabolic dunes (Semeniuk & Meagher 1981a)	bowls of parabolic dunes are excavated to a calcrete sheet formed above the water table (Semeniuk & Meagher 1981b); bowls therefore do not intersect water tables and hence no development of a dune slacks
parabolic dune fields, Bunbury to Busselton	dune barrier with eastward migrating parabolic dunes (Semeniuk & Meagher 1981a; Searle & Semeniuk 1985)	bowls of parabolic dunes are excavated to calcrete sheet formed above the water table (Semeniuk & Meagher 1981b); bowls therefore do not intersect water tables
parabolic dunes, seaward Scott Coastal Plain	dune barrier with northward ingressing parabolic dunes	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks
parabolic dunes, seaward D'Entrecasteaux area	dune barrier with northward ingressing parabolic dunes	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks; locally dune lakes are present
parabolic dunes, Circus Beach Barrier	dune barrier with northward ingressing parabolic dunes	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks; wetland on the barrier is a dune lake
parabolic dunes, Bellanger Barrier	dune barrier with northward ingressing parabolic dunes	the parabolic dunes and their bowl excavations are too high above the water table to form dune slacks
series of parabolic dunes, west of Bremer Bay (*i.e.*, Cape Knob Dunes, Dillon Bay Dunes, and James Cove Dunes)	inland ingressing parabolic dune fields encroaching on Precambrian rock headlands, or Pleistocene limestone, or Tertiary plateau	dune bowls expose underlying rocky basement and water is perched directly on rock and wetlands develop; the system is not a dune slack environment (Figure 15)
parabolic dunes, west of Esperance	inland ingressing parabolic dune fields encroaching on Pleistocene limestone	dune bowls expose underlying limestone and soils; where water is perched, the terrain is moistened but wetlands are not developed; the system is not a dune slack environment
parabolic dunes, east of Esperance	inland ingressing parabolic dune field, with erosion exposing cemented sheet of beach sand some 2 m above present sea level; wind erosion incising the cemented sheet formed a terrain of small mesas; the surrounding lowlands are windows to a water table	the wetlands exposed between the small mesas are in a fixed erosional topography and not a mobile dune system; as such, this system, though in a parabolic dune terrain, is not a dune slack environment
chaots and parabolic dunes, Dunn's Creek, Cape Arid area	chaot dune terrain and local parabolic dunes that bar Dunn's Creek which meanders, bifurcates, and winds through the dune field; the lowlands are wetlands	wetlands between the dunes are mainly recharged by fluvial surface water but also are partly windows to a water table elevated by fluvial input; though in a dune terrain, the wetlands are not in a dune slack environment

dune slacks, as there will be an inherent content of Fe, P and other elements in "immature" sediments and soils. Parent sand composition will partly determine the pH of dune slack water (C A Semeniuk 2007), a factor generally not addressed in studies overseas, though pH of dune slack water is a factor used to assess the "maturity" of a dune slack.

Importantly, this paper has set limits to where dune slacks cease, based on coastal processes and wetland processes. Coastal dune settings themselves will evolve with further erosion or progradation of the coast, and there is the potential for former stranded, stabilised and vegetated dune fields to become reactivated as they, in turn, front the coastline as part of ongoing coastal erosion. There is equally the propensity for coastal progradation to occur where seaward barriers form, or where sand supplies locally increase, due to deposition at a site or across the path of along shore coastal drift.

Coastal dune wetlands, if they are undisturbed, can evolve into more independent wetlands, with internal mechanisms of recharge becoming more pronounced than the previous open through-flow systems, altering

wetland hydroperiods, and causing adjustments in sedimentary deposition style, diagenesis, hydrochemistry, and plant responses. When this occurs, it is considered that the phase of dune slack maintenance and evolution has ceased, and a more complex wetland type is developing. To provide guidance in recognizing the limits of dune slack development, this paper describes where there are the dune slacks, where there are former dune slacks, and why dune slacks are not developed in a variety of other coastal dune fields.

On a final note, this paper, with its geomorphic, hydrologic, and hydrochemical approach to dune slacks at sub-continental scale provides, in combination with biogeography and regional biodiversity of Western Australia, a structure for developing a regional and local habitat framework for plant assemblages of dune slacks of Western Australia.

Acknowledgements: This paper is part of VCSRG's R&D endeavour into wetlands, registered as Project # 3 with AusIndustry.
We would like to thank Professor Ab Grootjan for providing a copy and translation of Van Dieren's 1934 original work on dune slacks.

References

Avis, A M & Lubke R A 1996 Dynamics and succession of coastal dune vegetation in the Eastern Cape, South Africa. Landscape & Urban Planning 34: 237–254.

Bakker T W M 1990 The geohydrology of coastal dunes. In: Dunes of the European Coasts (eds T W M Bakker, P D Jungerius & J A Klijn). Catena Supplement 18: 109–119.

Baxter J L 1977 Heavy Mineral Sand Deposits of Western Australia, Geological Survey of Western Australia. Mineral Resource Bulletin 10.

Bayly I A E & Williams W D 1973 Inland waters and their ecology. Longman, Melbourne.

Beard J A 1980 A new phytogeographic map of Western Australia. Research Notes, Western Australian Herbarium 3: 37–58.

Beeftink W G 1977 The coastal salt marshes of western and northern Europe: an ecological and phytosociological approach. In: Wet Coastal Ecosystems. Ecosystems of the World I (ed V J Chapman). Elsevier Scientific Publishing Company, Amsterdam, 109–156.

Bird E C F 1985 Victoria. In: The World's Coastline (eds E C F Bird & M L Schwartz). Van Nostrand Reinhold Co, New York, 899–911.

Bird E C F & Schwartz M L (eds) 1985 The World's Coastline. Van Nostrand Reinhold Co, New York.

Boorman L A 1993 Dry coastal ecosystems of Britain: dunes and shingle beaches. In: Ecosystems of the World. Dry Coastal Ecosystems 2A: Dry coastal ecosystems of Polar regions and Europe (ed E Van der Maarel). Elsevier, Amsterdam, 197–228.

Boorman L A Londo G & van der Maarel E 1997 Communities of dune slacks. In: Ecosystems of the World Dry Coastal Ecosystems 2C: General Aspects (ed E van der Maarel). Elsevier, Amsterdam, 275–295.

Botha G & Porat N 2007 Soil chronosequences development in dunes on the southeast African coastal plain, Maputaland, South Africa. Quaternary International 162–163: 111–132.

Brocx M & V Semeniuk 2010 Coastal geoheritage: a hierarchical approach to classifying coastal types as a basis for identifying diversity and sites of significance in Western Australia. Journal of the Royal Society of Western Australia 93: 81–113.

Brocx M & Semeniuk V 2011 The global geoheritage significance of the Kimberley Coast, Western Australia. Journal of the Royal Society of Western Australia 94: 57–88.

Carter R W G & Wilson P 1988 Geomorphological, sedimentological and pedological influences on coastal dune development in Ireland. Journal of Coastal Research Special Issue No 3: 27–31.

Castillo S, Popma J & Marino-Casasola P 1991 Coastal sand dune vegetation of Tabasco Campeche, Mexico. Journal of Vegetation Science 2(1): 73–88.

Chapman V J 1964 Coastal Vegetation. Pergamon Press, New York, 245.

Cordazzo C U & Seeliger U 1988 Phenological and biogeographical aspects of coastal dune plant communities in Southern Brazil. Vegetatio 75(3): 169–173.

Crawford R M M & Wishart D 1966 A multivariate analysis of the development of dune slack vegetation in relation to coastal accretion at Tentsmuir Fife. Journal of Ecology 54: 729–744.

de Raeve F 1987 Sand dune vegetation and management dynamics. In: Perspectives in coastal dune management (eds F van der Meulen, P D Jungerius & J H Visser). Proceedings of European Symposium 1987 Leiden, Netherlands.

Dickinson K J M & Mark A F 1994 Forest wetland vegetation patterns associated with a Holocene dune-slack sequence Haast Ecological District, south western New Zealand. Journal of Biogeography 21(3): 259–281.

Environment Australia 2007 Revision of the Interim Biogeographic Regionalisation for Australia (IBRA) and Development of Version 5.1 – Summary Report. Department of Environment & Heritage, Canberra.

Espejel I 1987 A phytogeographical analysis of coastal vegetation in the Yucatan Peninsula. Journal of Biogeography 14 (6): 499–519.

Freitas M C, Andrade C, Ferreira T, Cruces A & Araujo M F 2007 Wet dune slacks, sea level and coastal evolution in the South-western Portugese Façade. Journal of Coastal Research. Special Issue 50: 231–236.

Gentilli J 1972 Australian Climate Patterns. Nelson, Melbourne.

Grootjans A P, Lammerts E J & van Beusekom F (1995) Calcareous Dune Slacks of the Dutch Wadden Sea Islands. KNNV publishers, Utrecht, p176.

Grootjans A P, Sival F P & Stuyfzand P J 1996 Hydro-geochemical analysis of a degraded dune slack. Vegetatio 126: 27–38.

Grootjans A P, Ernst W H O & Stuyfzand P J 1998 European dune slacks: strong interactions of biology, pedogenesis and hydrology. Trends in Ecology & Evolution 13(3): 96–100.

Grootjans A P, Adema E, Bekker R & Lammerts E 2008 Why coastal dunes sustain a high biodiversity. In: Ecological Studies Coastal Dunes (eds M L Martinez & N P Psuty). Ecology & Conservation 171: 85–101.

Hellemaa P 1998 The development of coastal dunes and their vegetation in Finland. Fennia 176(1): 111–221.

Hopper S D 1979 Biogeographical aspects of speciation in the south-western Australian flora. Annual Review of Ecology Systematics 10: 399–422.

Hopper S D & P Gioia, 2004 The Southwest Australian Floristic Region: evolution and conservation of a global hotspot of biodiversity. Annual Review of Ecology, Evolution & Systematics 34: 623–650.

Jackson J M 1985 Uruguay. In: The World's Coastline (eds E C F Bird & M L Schwartz). Van Nostrand Reinhold Co., New York, 79–83.

Jennings J N 1957 Coastal dune lakes as exemplified from King Island, Tasmania. Geography Journal 123: 59–70.

Johnson D P 1982 Sedimentary facies in an arid zone delta: Gascoyne delta, Western Australia. Journal of Sedimentary Petrology 52: 547–563.

Jones R & Etherington J R 1971 Comparative studies of plant growth and distribution in relation to waterlogging. Part IV. The growth of dune and dune slack plants. Journal of Ecology 59: 793–801.

Jones P S & Etherington J R 1987–1989 Ecological and physiological studies of sand dune slack vegetation, Kenfig Pool and Dune local nature reserve, Mid-Glamorgan, Wales, UK. In: Perspectives in Coastal Dune Management (eds F van der Meulen, P D Jungerius & J H Visser). Proceedings of European Symposium 1987, Leiden, Netherlands.

Lammerts E J, Sival F P, Grootjans A P & Esselink H 1992 Hydrological conditions and soil, buffering processes controlling the occurrence of dune slack species on the Dutch Wadden Sea Islands. In: Coastal dunes, Geomorphology, Ecology and Management for Conservation (eds R W G Carter, T G F Curtis & M J Sheehy-Skeffington). Balkema, Rotterdam, 265–272.

Lammerts E J & Grootjans A P 1997 Nutrient deficiency in dune slack pioneer vegetation: a review. Journal of Coastal Conservation 3: 87–93

Lammerts E J Maas C & Grootjans A P 2001 Groundwater variables and vegetation in dune slacks. Ecological Engineer 17: 33–47

Leentvaar P 1997 Communities of dune lakes. In: Ecosystems of the World Dry Coastal Ecosystems 2C. General Aspects (ed E van der Maarel). Elsevier, Amsterdam, 297–322.

Logan B W (ed) 1970 Carbonate Sedimentation and Environments Shark Bay Western Australia. American Association of Petroleum Geologists Memoir 13.

Logan B W (ed) 1974 Evolution and Diagenesis of Quaternary Carbonate Sequences, Shark Bay, Western Australia. American Association of Petroleum Geologists Memoir 22.

Lowry D C & Doepel J J G 1974 Israelite Bay 1:250,000 Sheet SI 51-7 and part of SI 51-11 and Explanatory Notes Geological Society of Western Australia Australian Government Services, Canberra.

Lubke R A & Avis A M 1982 Factors affecting the distribution of *Scirpus nodosus* plants in a dune slack community. South African Journal of Botany 1: 97–103.

Lundberg A 1993 Dry coastal ecosystems of central and south Norway. In: Ecosystems of the World. Dry Coastal Ecosystems 2A. Dry coastal ecosystems of Polar regions and Europe (ed E van der Maarel). Elsevier, Amsterdam, 109–130.

Lyons M N, Keighery G J, Gibson N & Wardell-Johnson G 2000 The vascular flora of the Warren bioregion, southwest Western Australia: composition, reservation status and endemism. CALMScience 3: 181–250.

McKee E D & Ward W C 1983 Aeolian environment. In: Carbonate depositional environments (eds P A Scholle D G Bebont & C H Moore). American Association of Petroleum Geologists (AAPG) Memoir 33, 131–170.

McLachlan A, Kerley G & Rickard C 1996 Ecology and energetics of slacks in the Alexandria coastal dunefield. Landscape & Urban Planning 34: 267–276.

Moreno-Casasola P 1988 Patterns of plant species distribution on coastal dunes along the Gulf of Mexico. Journal of Biogeography 15: 787–806.

Munoz Reinoso J C 2001 Sequential pattern in the stabilised dunes of Donana Biological Reserve (SW Spain). Journal of Coastal Research 17(1): 90–94.

Myers N, Mittermeier R A, Mittermeier C G, da Fonseca G A B & Kent J 2000. Biodiversity hotspots for conservation priorities. Nature 403: 803–808.

Outridge P M, Arthrington A H & Miller G J 1989 Limnology of naturally acidic, oligotrophic dune lakes in subtropical Australia, including chlorophyll – phosphorous relationships. Hydrobiologia 179: 39–51.

Ovington J D 1951 The afforestation of Tentsmuir sands. Journal of Ecology 39:363–375.

Pye K 1983 Coastal dunes. Physical Geography 7: 531–557.

Ranwell D S 1959 Newborough Warren, Anglesey. I The dune system and dune slack habitat. Journal of Ecology 47: 571–601.

Ranwell D S 1960 Newborough Warren, Anglesey. II Plant associations and succession cycles of the sand dune and dune slack vegetation. Journal of Ecology 48: 117–41.

Ranwell D S 1972 Ecology of salt marshes and sand dunes. Chapman & Hall, London, 258.

Ratcliffe D A 1977 A nature conservation review, Vols 1 & 2. Cambridge University Press, Cambridge.

Rodriguez-Ramirez A, Rodriguez-Vidal J, Caceres L, Clemente L, Belluomini G, Manfra L, Improta S & de Andres J R 1996 recent coastal evolution of the Donana national Park (SW Spain). Quaternary Science Reviews 15: 803–809.

Rozema J, Bijwaard P, Prast G & Broekman R 1985 Ecophysiological adaptations of coastal halophytes from foredunes and salt marshes. Vegetatio 62: 499–521.

Rozema J Laan P Broekman R 1985 On the lime content in the Dutch coastal sand dunes in the province of Noord-Holland. In: Ecology of Coastal vegetation. Proceedings of a Symposium, Haamstede (1983) Advances in Vegetation Science 6, (eds W G Beeftink, J Rozema & A H L Huiskes). Dr W Junk Publishers Dordrecht, 559–560.

Salisbury E J 1952 Downs and Dunes, Their Plant Life and its Environment. G Bell & Sons, London, 328.

Schat H 1984 A comparative ecophysiological study on the effects of waterlogging and submergence on dune slack plants: growth, survival and mineral nutrition in sand culture experiments. Oecologia 62: 279–286.

Scott P A 1985 Sierra Leone. In: The World's Coastline (eds E C F Bird & M L Schwartz). Van Nostrand Reinhold Co., New York, 569–573.

Searle D J & Semeniuk V 1985 The natural sectors of the inner Rottnest Shelf coast adjoining the Swan Coastal Plain. Journal of the Royal Society of Western Australia 67: 115–135.

Searle D J & Semeniuk V 1988 Petrology and origin of beach sand along the Rottnest Shelf coast, Southwestern Australia. Journal of the Royal Society of Western Australia 70(4): 119–128.

Searle D J Semeniuk V & Woods P J 1988 Geomorphology, stratigraphy and Holocene history of the Rockingham- Becher Plain, south-western Australia. Journal of the Royal Society of Australia 70(4): 89–109.

Semeniuk C A 1987 Wetlands of the Darling System – a geomorphic approach to habitat classification. Journal of the Royal Society of Western Australia 69: 95–111.

Semeniuk C A 1988 Consanguineous wetlands and their distribution in the Darling System, Southwestern Australia. Journal of the Royal Society of Western Australia 70(3): 69–87.

Semeniuk C A 2007 The Becher wetlands – a Ramsar site. Evolution of wetland habitats and vegetation associations on a Holocene coastal plain, south-western Australia. Volume 1–Wetlands: ecology, conservation and management. Springer, The Netherlands, 680.

Semeniuk C A & Semeniuk V 1995 A geomorphic approach to global classification for inland wetlands. Vegetatio 118: 103–124.

Semeniuk V 1993 The mangrove systems of Western Australia: 1993 Presidential Address. Journal of the Royal Society of Western Australia 76: 99–122.

Semeniuk V 1996 Coastal forms and Quaternary processes along the arid Pilbara coast of northwestern Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 123: 49–84.

Semeniuk V 2008 Sedimentation, stratigraphy, biostratigraphy, and Holocene history of the Canning Coast, north-western Australia. Journal of the Royal Society of Western Australia 91: 53–148.

Semeniuk V & Brocx M 2011 King Sound and the tide-dominated delta of the Fitzroy River: their geoheritage values. Journal of the Royal Society of Western Australia 94: 151–160.

Semeniuk V & Meagher T D 1981a The geomorphology and

surface processes of the Australind – Leschenault Inlet coastal area. Journal of the Royal Society of Western Australia 64: 33–51.

Semeniuk V & Meagher T D 1981b Calcrete in Quaternary coastal dunes in South Western Australia: a capillary-rise phenomenon associated with plants. Journal of Sedimentary Petrology 51: 47–68.

Semeniuk V & Searle D J 1986 The Whitfords Cusp-its geomorphology, stratigraphy and age structure. Journal of the Royal Society of Western Australia 68: 29–36.

Semeniuk V & Semeniuk C A 2004 Sedimentary fill of basin wetlands, central Swan Coastal Plain, southwestern Australia. Part l: sediment particles, typical sediments, and classification of depositional systems. Journal of the Royal Society of Western Australia 87:139–186.

Semeniuk V & Semeniuk C A 2006 Sedimentary fill of basin wetlands, central Swan Coastal Plain, southwestern Australia. Part 2: distribution of sediment types and stratigraphy. Royal Society of Western Australia 89: 185–220.

Semeniuk V, Chalmer P N & LeProvost I P 1982 The marine environments of the Dampier Archipelago. Journal of the Royal Society of Western Australia 65: 97–114.

Semeniuk V, Cresswell I D & Wurm P A S 1989 The Quindalup Dunes: the regional system, physical framework and vegetation habitats. Journal of the Royal Society of Western Australia 71(2 and 3): 23–47.

Semeniuk V, Semeniuk C A, Tauss C, Unno J & Brocx M 2011 Walpole and Nornalup Inlets: landforms, stratigraphy, evolution, hydrology, water quality, biota, and geoheritage. Western Australian Museum, Perth (Monograph). 584 p.

Serrano L, Reina M, Martin G, Reyes I, Arechederra A, Leon D & Toja J 2006 The aquatic systems of Donana (SW Spain): watersheds and frontiers. Limnetica 25(1–2): 11–32.

Short A D & Hesp P A 1982 Wave, beach and dune interactions in southeastern Australia. Marine Geology 48: 259–284.

Siljestrom P A & Clemente L E 1990 Geomorphology and soil evolution of a moving dune system in south west Spain (Donana National Park). Journal of Arid Environments 18: 139–150.

Siljestrom P A, Moreno A, Garcia L V & Clemente L E 1994 Donana National Park (southwest Spain): geomorphological characterisation through a soil vegetation study. Journal of Arid Environments 26: 315–23.

Sival F P 1996 Mesotrophic basiphilous communities affected by changes in soil properties in two dune slack chronosequences. Acta Botanica Neerlandica 45: 95–106.

Skudder III P A, Backus D H, Goodwin D H & Johnson M E 2006 Sequestration of carbonate shell material in coastal dunes on the Gulf of California (Baja California Sur Mexico) Journal of Coastal Research 22(3): 611–624

Sykora K V, van den Bogert C J M & Berendse F 2004 Changes in soil and vegetation during dune slack succession. Journal of Vegetation Science 15(2): 209–218.

Tansley A G 1949 The British Islands and their vegetation (Second Edition). Cambridge University Press, Cambridge.

Teh T S 1985 Peninsula Malaysia. In: The World's Coastline (eds E C F Bird & M L Schwartz). Van Nostrand Reinhold Co., New York, 789–795.

Thackway R, & Cresswell I D (eds) 1995 An Interim Biogeographic Regionalisation for Australia: a framework for establishing the national system of reserves. Version 4.0. Australian Nature Conservation Agency, Canberra.

Thompson C H 1981 Podzol chronosequences on coastal dunes of eastern Australia. Nature 291: 59–61.

Timms B V 1977 A study of some coastal dune lakes in western Victoria. Proceedings of the Royal Society of Victoria 89: 167–72.

Timms B V 1982 Coastal dune waterbodies of northeastern New South Wales. Australian Journal of Marine and Freshwater Research 33: 203–222.

Timms B V 1986 Reconnaissance Limnology of some coastal dune lakes of Cape York peninsula, Queensland.. Australian Journal of Marine and Freshwater Research 37: 167–176.

Timms B V 1997 Study of coastal freshwater lakes in southern NSW. Australian Journal of Marine and Freshwater Research 48(3): 249–256.

Tinley K L 1985a Coastal dunes of South Africa. South Africa National Scientific Programmes Report No 109.

Tinley K L 1985b Mozambique. In: The world's coastline (eds E C F Bird & M L Schwartz). Van Nostrand Reinhold Co., New York, 669–677.

Trewartha G T 1968 An introduction to climate (4th Edition). McGraw-Hill Book Company, New York.

UK Joint Nature Conservation Committee 2009 Special areas of conservation. Annexe 1 Habitat accounts – humid dune slacks.

Usoro E J 1985 Nigeria. In: The World's Coastline (eds E C F Bird & M L Schwartz). Van Nostrand Reinhold Co., New York, 607–613.

V & C Semeniuk Research Group 1991 Wetlands of the City of Rockingham: Their classification, significance and management. Report to City of Rockingham and Heritage Council of Western Australia Perth, WA.

V & C Semeniuk Research Group 1994 Ecological assessment and evaluation of wetlands in the System 5 region. Report to West Australian Heritage Commission, Perth WA.

V & C Semeniuk Research Group 1997a Consanguineous wetland suites between Albany and Bremer Bay. Report to Water & Rivers Commission, Perth WA.

V & C Semeniuk Research Group 1997b Mapping and classification of wetlands from Augusta to Walpole in the south west of Western Australia. Report to Water and Rivers Commission. Water Resources Technical Series Report No WRT 12 Perth, WA.

V & C Semeniuk Research Group 2000 Consanguineous suites of the Great Sandy Desert wetland region. Report to Water & Rivers Commission Perth, WA.

V & C Semeniuk Research Group 2006 Wetlands mapping, classification, and evaluation – south west W5-01 region. Report to Department of Environment and Conservation, Perth, WA.

V & C Semeniuk Research Group 2007 Wetlands mapping, classification, and evaluation on the Leeuwin Naturaliste Ridge. Report to the Department of Environment and Conservation, Perth, WA.

V & C Semeniuk Research Group 2008 Wetland mapping and classification Manjimup to Northcliffe Report to Department of Environment and Conservation, Perth, WA.

van den Berg J A & Ullersma P 1994 Ponded infiltration as a cause of the instability of continuous macropores. Journal of Hydrology 159: 169–186.

van der Laan D 1979 Spatial and temporal variation in the vegetation of dune slacks in relation to the groundwater regime. Vegetatio 39(1): 43–51.

van der Meulen F & van der Maarel E 1989 Coastal defense alternatives and nature development perspectives. In: Perspectives in coastal dune management (eds F van der Meulen, P D Jungerius & J Visser). SPB Academic Publishers, The Hague, 183–195.

van der Meulen F & van der Maarel E 1993 Dry coastal ecosystems of the central and southwestern Netherlands. In: Ecosystems of the World Dry Coastal Ecosystems 2A. Polar regions and Europe (ed E van der Maarel). Elsevier, Amsterdam, 271–315.

van Dieren J W 1934 Organogene dunenbildung, eine geomorphologische analyse der westfriesischen Insel Terschelling mit pflanzensociologischen methoden. Nijhoff Den Haag NL.

van Dijk H W J & Grootjans A P 1993 Wet dune slacks: decline and new opportunities. Hydrobiologia 265: 281–304.

van Huis J 1989 European dunes, climate and climate change, with case studies of the Coto Donana (Spain) and the Slowinski (Poland) National Parks. In: Perspectives in coastal dune management (eds F van der Meulen, P D Jungerius J & Visser). Proceedings of the European Symposium 1987, The Netherlands, 313–326.

Ward W T 2006 Coastal dunes and strandplains in southeast Queensland: sequence and chronology. Australian Journal of Earth Sciences 53: 363–373.

Westoff V 1954 Een en ander over het onstaan en de plantengroei van duinmeertjes. Report Lab. Voor plantensystematiek en geografie Wageninen, 5.

Westoff V 1989 Dunes and dune management along the North Sea coasts. In: Perspectives in coastal dune management (eds F van der Meulen, P D Jungerius J & Visser). Proceedings of the European Symposium 1987, The Netherlands, 41–52.

Wiedemann A M 1993 Dry coastal ecosystems of northwest North America. In: Ecosystems of the World Dry Coastal Ecosystems 2B. Africa America, Asia and Oceania (ed E van der Maarel). Elsevier, Amsterdam, 341–358.

Willis A J, Folkes J F, Hope-Simpson J F & Yemm E W 1959a Braunton Burrows: the dune system and its vegetation. Part I. Journal of Ecology 47(1): 11–24.

Willis A J Folkes J F Hope-Simpson J F & Yemm E W 1959b Braunton Burrows: The dune system and its vegetation. Part II. Journal of Ecology 47(2): 249–288.

Yan Q, Liu Z, Ma J & Jiang D 2006 The role of reproductive phenology, seedling emergence and establishment of perennial *Salix gordejevii* in active sand dune fields. Annals of Botany 99(1): 19–28.

Journal of the Royal Society of Western Australia, 94: 533–539, 2011

Influence of habitat characteristics on the distribution of the water-rat (*Hydromys chrysogaster*) in the greater Perth region, Western Australia

C Smart [1], P C Speldewinde [2] & H R Mills [1]

[1] School of Animal Biology, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009

[2] Centre of Excellence in Natural Resource Management, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009

Manuscript received August 2010; accepted May 2011

Abstract

This study investigated the distribution of the water-rat (*Hydromys chrysogaster*) in the greater Perth region, and proposes the potential of the species as a bioindicator of habitat quality. The degradation and loss of wetlands on the Swan Coastal Plain are associated with changes to habitat quality, including vegetation cover, stream cover, habitat diversity and bank stability. The occurrence of *H. chrysogaster* was analysed with respect to these factors at various water bodies around the greater Perth area. Sites positive for the presence of *H. chrysogaster* correlated with high value habitat quality characteristics, including high bank stability, habitat diversity, stream cover and foreshore vegetation. The presence of *H. chrysogaster* was not correlated to the occurrence and abundance of other local mammal species, except for a positive relationship with the introduced black rat (*Rattus rattus*) in relation to abundance. Based on the habitat requirements of *H. chrysogaster*, the species has some potential as a bioindicator of wetland condition on the Swan Coastal Plain, Western Australia, although the viability of such a method is uncertain.

Key words: wetland, habitat quality, bioindicator, rakali, Swan Coastal Plain

Introduction

Effective conservation of biodiversity in urbanised wetland areas requires an in-depth understanding of how aquatic species respond to changing habitat quality, water seasonality, and pollutant concentrations. Mammals have been used on numerous occasions as bioindicators of habitat quality, and this is especially true of small mammals such as rodents (Wren 1986). The water-rat (*Hydromys chrysogaster* Geoffroy 1804) is a native, semi-aquatic mammal that is common in some urbanised areas and especially in irrigation channels in the Eastern states of Australia (McNally 1960). Valentine *et al.* (2009) suggested that the success of populations of *H. chrysogaster* is critically linked with the persistence of important wetland ecosystems, and as a result *H. chrysogaster* may be used as an indicator species for Western Australian wetlands. Seventy percent of wetlands on the Swan Coastal Plain have disappeared since European settlement due to infilling, land clearing and over-drainage (Balla & Davis 1993; Davis *et al.* 1993). Of those remaining, many have become nutrient-enriched, saline, urbanised, subject to excessive groundwater extraction or contaminated by heavy metals and pesticides (Hill *et al.* 1996; Environment Australia 2001). Atkinson *et al.* (2008) hypothesised that vast degradation and salinisation of south-western water systems has lead to a substantial decline in western populations of *H. chrysogaster*. However, ecological studies on the health and abundance of Western Australian populations of the water-rat are few, especially in consideration of the current state of the wetlands on the Swan Coastal Plain.

Suitability of habitat is thought to be one of the factors influencing the distribution of mammals (Geier & Best 1980). Permanent water bodies on the Swan Coastal Plain have undergone detrimental habitat changes due to such processes as urbanisation, clearing, drainage, and livestock grazing (Davis *et al.* 1993). Habitat requirements for *H. chrysogaster* include areas suitable for dens or burrows (steep banks and/or logs) and some degree of vegetation cover (Scott & Grant 1997; Weir 2004). Previous trapping efforts for the species have been more successful where vegetated islands or reed beds were present close to the main bank (Valentine *et al.* 2009). However, no previous study has formally investigated the habitat requirements of *H. chrysogaster* and if these characteristics are related to habitat quality.

Habitat loss and fragmentation are significant factors contributing to species loss in south-western Australia, including frogs, waterbirds and mammals (GSS 2009). Pamment (1986) recorded 50 % of water-rat captures at man-made ponds, and Gardner and Serena (1995) recorded one-third of captures along similar, urbanised areas. Therefore, being common in urban, man-modified systems (Gardner & Serena 1995), *H. chrysogaster* is likely to be impacted by changes to water and habitat quality in urbanised catchments. Semi-aquatic mammals are in a "precarious" ecological niche because of the changing condition of water systems on the Swan Coastal Plain, in particular declining rainfall and groundwater levels that may also lead to decreased connectivity between wetland systems (Valentine *et al.* 2009). Declines in the number and size of populations of both water-rats and bush rats (*Rattus fuscipes*) on the Gnangara Mound, an important groundwater system, are possibly due to changes in permanent wetlands around Perth as a result of declining

rainfall (GSS 2009). However, there are inconsistencies in the literature over the permanency of water required for *H. chrysogaster*, ranging from the species being able to survive on dry land and migrate long distances in agricultural areas (McNally 1960; Vernes 1998) to the requirement of permanent water (Scott & Grant 1997; Valentine *et al.* 2009). While these differences may be attributable to seasonal changes in behaviour, we do not have sufficient data to be sure. Hence the effects of habitat disturbance on this species are not well understood.

Effective conservation of urbanised wetlands requires an in-depth understanding of how well species adapt to changing habitat quality (bank stability, vegetation cover, habitat diversity, stream cover) and habitat structure (area, permanency of wetland), including the presence of other species. This study investigated the relative importance of these environmental and biological factors on the distribution of water-rats in the greater Perth region, Western Australia. This is particularly important in light of the degradation of many wetlands and lakes on the Swan Coastal Plain, and due to the species' position as a top order predator in these systems it may be used as a bio-indicator of the system quality. We investigated whether habitat structure and habitat quality contribute to the probability of *H. chrysogaster* presence.

Materials and Methods

Study Sites

Thirty-nine wetlands were investigated in the greater Perth metropolitan area, Western Australia, over a consecutive 13-week period (n = 3421 trap nights) from July to September 2009. The wetland study sites were both north and south of the Canning River running through the city centre, and were bordered by Yanchep National Park north of Perth, Rockingham to the south, and Mundaring in the Perth hills to the east of the main city (Fig. 1). Sites chosen were considered representative of the current state of lakes and wetlands in the greater Perth metropolitan area based on the wetland type, size and proximity to urbanised areas.

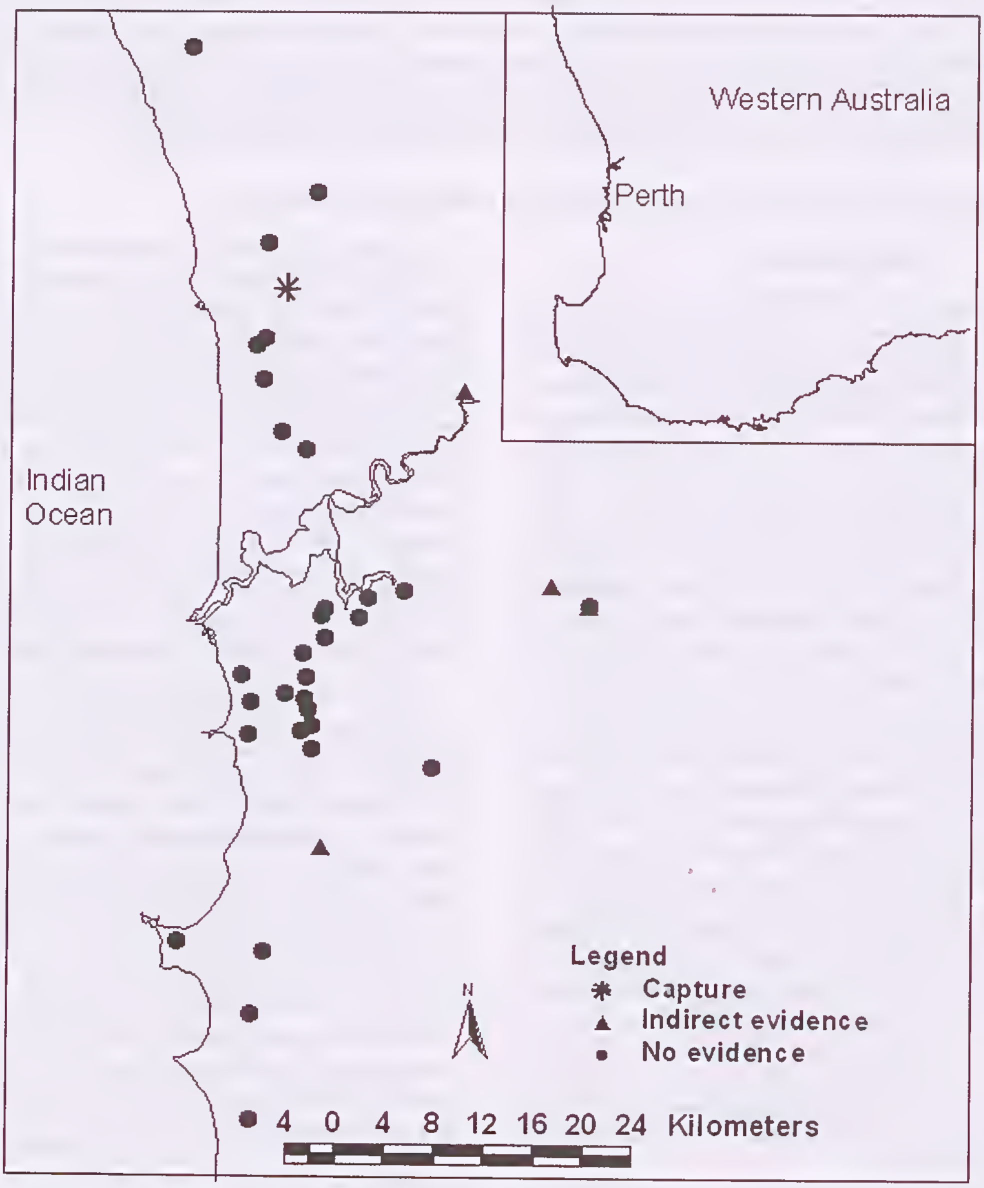


Figure 1. Map of sampling sites in the greater Perth region showing records of *Hydromys chrysogaster* as of October 2009.

Habitat Type

At each site, habitat quality characteristics were assessed by visual observation using the methods of Shepherd and Siemon from the Water and Rivers Commission (1999), with consideration of the EPA Bulletin *A Guide to Wetland Management in the Perth and Near Perth Swan Coastal Plain Area* (1993). Using these methods, four main habitat quality variables (vegetation cover, habitat diversity, stream cover, bank stability) were assessed, where each variable was given a condition index ranging from 0 (very poor) to 8 (excellent) based on a set of given parameters.

Water level data (Australian Height Datum; AHD m) were based on the records of the Department of Water (2005–2009). The average minimum water depth of each study site from the previous five years (2005–2009) was used to indicate the permanency of the water source, where water levels below 0.5 m were considered to be seasonally low. The area of open water of each study site (km^2), smallest distance between sites, and distance to the nearest water body from a site with *H. chrysogaster* was estimated using Google Earth Pro (Version 5.0).

Animal trapping

Wire cage traps were set at each site (n = 20–50/site) and baited with whole previously frozen pilchards. Traps were set at 20 m spacing across a continuum of habitat types, and set for 3–4 nights per site (3421 trapnights) from July (winter) to late September (spring). All traps were set facing the water and within 2 m of the water's edge.

Visual surveys were conducted along the trapped area of each study site for evidence of *H. chrysogaster* presence. These surveys were conducted daily and included observations of footprints, scats and the presence of feeding middens. Photographic evidence was taken of any visual signs of water-rat presence so that identification could later be double-checked against a field guide (Triggs 2004) or by other experts. Evidence of *H. chrysogaster* presence was supplemented by historical records of sightings and specimens provided by the Western Australian Museum dating from 1975, as well as from the management plans relevant to each wetland or lake. All non-target species trapped were noted, both native and introduced, as well as evidence of water-rat presence including scats, footprints and previous sightings.

Results

Evidence of *H. chrysogaster* was found at 7 of the 39 sites surveyed (18 %). This included direct captures at two sites (Lake Goollelal and Lake Joondalup [North]), captures by the Department of Environment and Conservation (Valentine *et al.* 2009) in the previous year at one site (Loch McNess), and evidence of presence at four sites (Canning River, Spectacles wetlands, Bennett Brook, Bickley Brook).

The size of each wetland sampled ranged from 0.02 km^2 to 4.26 km^2 (Table 1), where the average wetland size for positive sites was 2.0 ± 0.44 km^2. Binary logistic regression found a positive correlation between the presence of *H. chrysogaster* and the size of the wetland in

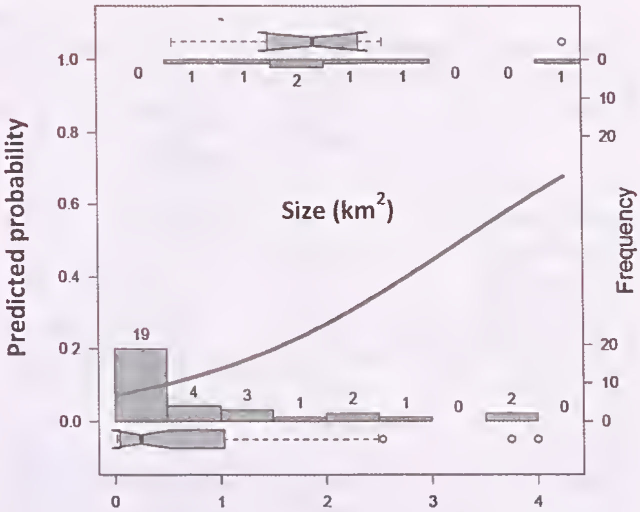


Figure 2. Nominal logistic regressions of size of wetland with *H. chrysogaster* occurrence (R^2 = 0.152, p = 0.018). Occurrence of *H. chrysogaster* is the designated y-variable where presence = 1 (n = 7) and absence = 0 (n = 32). Number of sites within each size category are labelled above each bar. ** denotes statistical significance α = 0.05

which they were found (R^2 = 0.153, p = 0.018), indicating that the species may be more numerous where water sources are larger in area (Fig. 2).

Positive sites (sites with *H. chrysogaster* presence) were highly varied in distribution around the greater Perth area, ranging in proximity from 5–75 km apart ($\bar{x}$ = 31.95 ± 3.71 km). The average distance between a positive site and the nearest water body was 2.77 ± 0.93 km.

The occurrence of *H. chrysogaster* at the study sites was analysed in relation to the permanency of the water source, measured by the minimum water level (AHD m) since 2005. The logistic regression between these two variables was not significant (R^2 = 0.077, p = 0.598). A minimum water depth of 0.94 m was the lowest water level recorded since 2005 for any site supporting a population of *H. chrysogaster*.

The habitat quality scores for each parameter were significantly different between sites with and without *H. chrysogaster* (ANOVA, p = 0.006; Table 1). The seven positive sites formed a relatively tight group within this principal component space and therefore embrace similar environmental conditions in terms of habitat quality (Fig. 3). Increases in Component 1 reflected increasing vegetation cover (%), habitat diversity and stream cover, whereas increases in Component 2 reflected greater bank angle and stability. All core sites scored highly for Component 1, and half scored highly for Component 2. This observation was confirmed using 2-sample t-tests, where for both Component 1 (t-test, p = 3.22 x 10^{-7}) and Component 2 (t-test, p = 0.038), the sites positive for *H. chrysogaster* differed in their principal component values from those sites without *H. chrysogaster*. The sites with evidence of *H. chrysogaster* presence had higher vegetation coverage (79%) than those sites without *H. chrysogaster* (54 %) (t-test, p < 0.001). Sites with *H. chrysogaster* had steeper bank angles (60.0°) than those without any evidence of *H. chrysogaster* presence (19.7°) (t-test, p <0.001).

Table 1

Summary data of habitat variables for wetland sites positive and negative for the presence of Hydromys chrysogaster.

Positive	Size (km2)	Min water depth (AHD m)	Veg cover (%)	Bank angle	Bank stability	Stream cover	Habitat diversity
Bennett Brook	1.90	6.78	65	90	8	6	6
Bickley Brook	0.56	9.90	90	70	8	8	6
Canning River	1.64	0.94	75	80	8	8	6
Lake Goolellal	2.10	26.50	80	50	6	8	8
Lake Joondalup (North)	4.26	16.0	85	30	8	8	8
Loch McNess	2.55	6.60	75	70	8	6	6
The Spectacles	1.30	8.60	85	30	6	8	8
Average ± se	*2.0 ± 0.44*	*10.8 ± 3.13*	*79.3 ± 3.16*	*60.0 ± 8.99*	*7.4 ± 0.37*	*7.4 ± 0.37*	*6.9 ± 0.40*
Negative	**Size (km2)**	**Min water depth (AHD m)**	**Veg cover (%)**	**Bank angle**	**Bank stability**	**Stream cover**	**Habitat diversity**
Anstey Swamp	2.49	1.85	60	0	4	8	2
Bibra Lake	1.24	13.54	50	20	4	6	8
Blue Gum Lake	0.02	5.00	35	10	2	4	2
Booragoon Lake	0.04	10.00	55	20	4	6	2
Bull Creek	0.02	1.00	65	70	2	8	4
Carine Swamp	0.18	3.00	65	10	6	6	6
Forrestdale Lake	1.06	21.60	45	10	2	6	4
Herdsman Lake	2.40	6.32	35	0	4	8	8
Kogolup Lake (North)	0.35	3.00	60	30	6	6	6
Kogolup Lake (South)	0.12	3.00	65	30	6	6	6
Lake Coogee	0.52	0.17	45	40	6	4	6
Lake Cooloongup	3.75	1.42	60	40	6	6	8
Lake Gwelup	0.14	5.00	50	10	6	4	4
Lake Jandabup	2.53	44.10	80	0	6	8	6
Lake Joondalup (South)	0.14	3.00	70	20	2	8	6
Lake Marginup	1.01	41.17	70	10	4	8	4
Lake Monger	0.65	0.90	40	20	4	4	4
Lake Nowergup	0.29	16.09	55	10	4	6	6
Lake Richmond	0.27	0.14	45	40	4	6	6
Lake Walyungup	4.00	0.70	10	10	4	0	2
Little Rush Lake	0.04	2.50	70	10	6	6	6
Little Carine Swamp	0.03	5.00	50	70	6	6	6
Manning Lake	0.05	0.11	65	0	2	4	6
Market Garden Swamp	0.03	0.11	45	20	6	4	4
Mundaring Weir	0.67	20.30	40	20	6	0	4
North Lake	0.22	12.38	60	10	4	6	6
Piney Lakes	0.15	2.20	60	0	2	8	6
Quenda Wetlands	0.02	2.10	75	30	6	6	4
South Lake	0.02	5.38	80	20	4	6	8
Thomsons Lake	1.91	10.70	35	0	6	8	6
Victoria Reservoir	0.21	18.20	40	20	6	0	4
Yangebup Lake	0.75	2.50	65	30	6	4	4
Average ± se	0.8 ± 0.20	8.2 ± 1.94	54.5 ± 2.72	19.7 ± 3.16	4.6 ± 0.27	5.5 ± 0.42	5.1 ± 0.31

There was only one site with evidence of *H. chrysogaster* where southern brown bandicoots (*Isoodon obesulus*) were also detected. However at sites where there was no evidence of water-rats, southern brown bandicoots were recorded at 12 of 32 sites, with up to 13 captures within a week (Fig. 4). This trend was not significant for the occurrence (chi-square, $p=0.238$) or abundance (t-test, $p = 0.164$) of bandicoots caught at sites with and without *H. chrysogaster*. In contrast, the introduced black rat (*Rattus rattus*) was captured at all sites with *H. chrysogaster* presence (Fig. 4), with a significant positive relationship (chi-square, $p = 0.001$). *R. rattus* was also captured at 11 of 32 sites without *H. chrysogaster*. A positive trend also existed for the

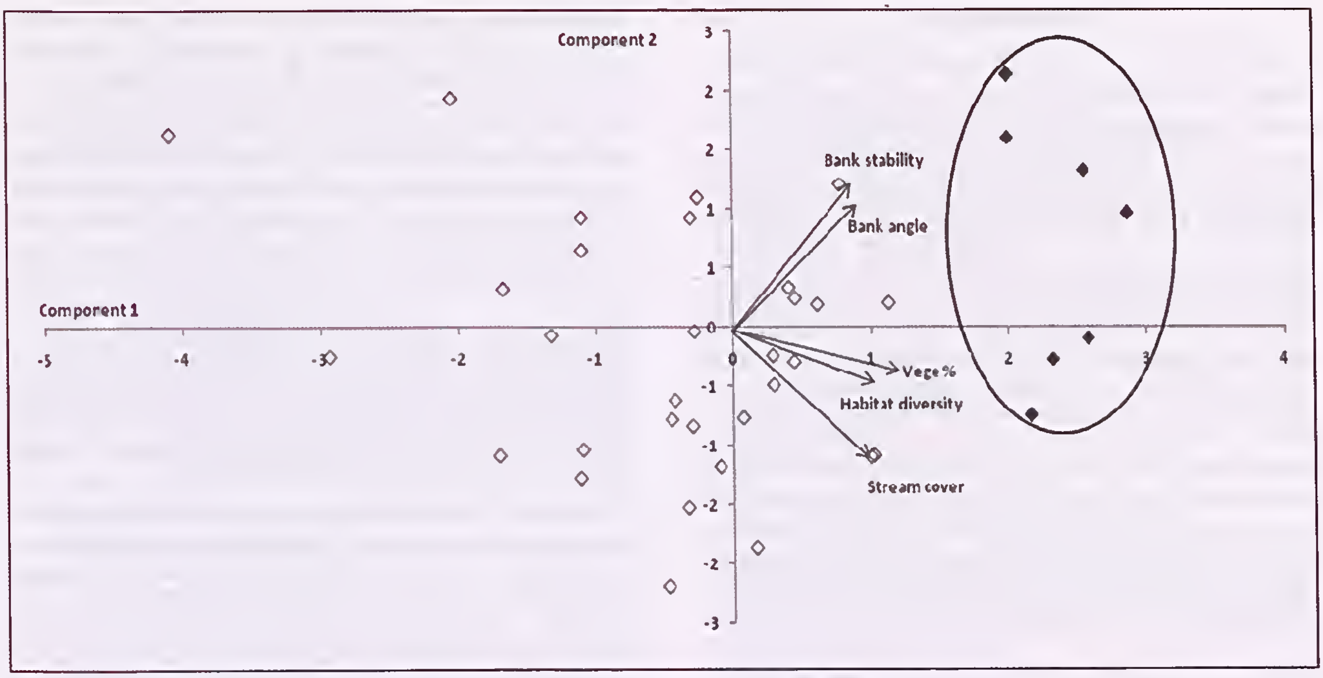


Figure 3. Principal Component Analysis of sites: Components I and 2. Positive sites (n = 7) are grouped with black markers and circled. A bi-plot from the origin identifies the trend of each habitat variable in relation to each component. Positive sites are significantly different in both Component 1 ($p = 3.32 \times 10^{-7}$) and Component 2 ($p = 0.038$) values compared to negative sites (n = 32). Significance is set as $\alpha = 0.05$

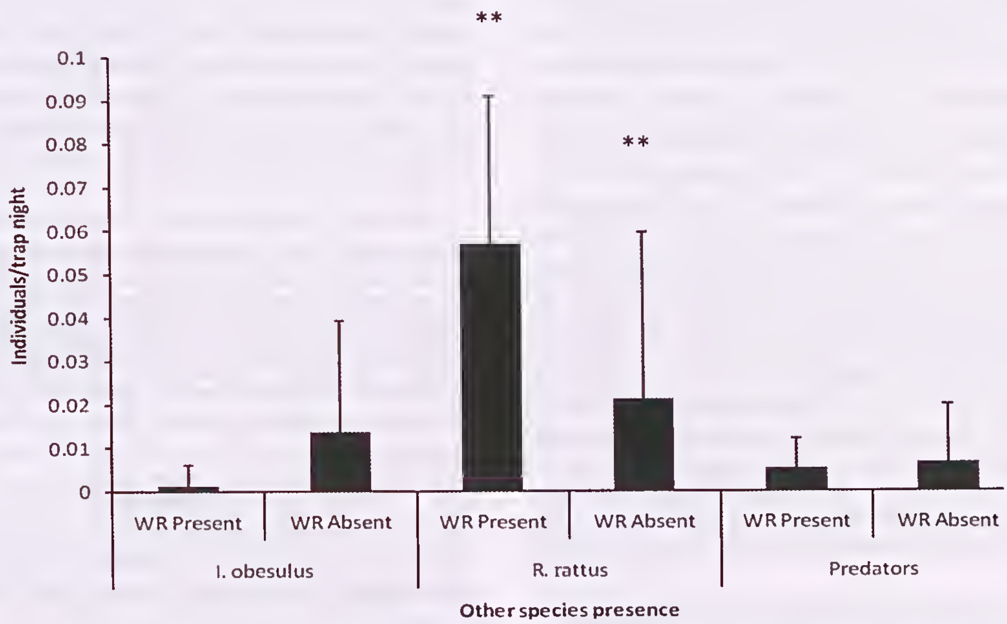


Figure 4. Presence of other species (individuals/trap night) in relation to the presence of WR (water-rats). Other species included are southern brown bandicoots (*I. obesulus*), black rats (*R. rattus*) and predators (cats, snakes, dogs, foxes, raptors). Species abundances are ± standard error. ** denotes statistical significance $\alpha = 0.05$

number of *R. rattus* (individuals/trap night) caught at sites with and without *H. chrysogaster* (t-test; $p < 0.001$).

Predator species recorded during the study included domestic cats (*Felis catus*), tiger snakes (*Notechis scutatus*), Australian ravens (*Corvus coronoides*), European red foxes (*Vulpes vulpes*), domestic dogs (*Canis lupus familiaris*) and raptorial birds such as wedge-tailed eagles (*Aquila audax*).

Three of the seven sites with water-rats and 12 of 32 negative sites, had strong evidence of predator occurrence. No significant relationship existed between the occurrence of predator species (chi-square, $p = 0.792$) or abundance of predators (t-test, $p=0.714$) observed per trap night between sites with and without *H. chrysogaster* (Fig. 4).

Discussion

The striking feature of this study was the low numbers of water-rats captured, especially at sites where populations are known to persist. This study captured two individuals at Lake Goollelal and none at Loch McNess, where 11 and 5 captures were made respectively in autumn 2008 using similar methods (Valentine *et al.* 2009). Trapping can be an unreliable method of measuring abundance in some species. It has been suggested that *H. chrysogaster* is easily captured only where individuals are numerous (Valentine *et al.* 2009) and that capture success rate is seasonal (Harris 1978). Harris (1978) found that there were fewer captures than expected for males during winter, spring and summer, and for females fewer captures were made during winter and spring. This may be due to reductions in population sizes during the year following autumn due to social stress and reduced activity patterns in response to depleted food resources. Drops in water temperature may contribute to these lower feeding activity patterns, as water-rats are unable to regulate their body temperature effectively (Fanning & Dawson 1980). By contrast, autumn is the peak season for young to disperse and as a result more individuals are observed (Harris 1978). Therefore, small population sizes due to seasonality may have contributed to the low capture success rate here.

The results indicate that the presence of *H. chrysogaster* in Perth is linked to a number of different habitat quality characteristics. A positive correlation was found between the size of the wetland and the presence of water-rats, where the average study site size for positive sites was 2.04 km^2. Home range sizes of the species have been recorded between 0.9 km^2 (Harris 1978) to 3.9 km^2 (Gardner & Serena 1995), where individuals can use between 0.4 km^2 (Harris 1978) to 3.1 km (Gardner & Serena 1995) of habitat in a single night. These studies were, however, conducted on Eastern states populations of *H. chrysogaster*, and may not be representative of populations in south-western Australia. The smallest site with evidence of *H. chrysogaster* in this study was 0.56 km^2 (Bickley Brook), although this site is connected to the Canning River to provide a broader water source (up to 21 km^2). It can be concluded that in order to sustain a viable population of *H. chrysogaster*, the size of the water source must be large to incorporate the localized movement patterns and intra- and inter-sexual territoriality recorded for the species (Gardner & Serena 1995).

Although all sites with evidence of *H. chrysogaster* were permanent water sources, no statistical trend was observed between water depth and species presence. Most literature describing observations of *H. chrysogaster* in Australia have outlined the importance of permanent water for the species (see Scott & Grant 1997; Valentine *et al.* 2009) although they have been recorded in temporary water sources (Atkinson *et al.* 2008). Harris (1978) reported that *H. chrysogaster* rarely hunted in waters deeper than two metres, preferring to forage in proximity to the shore. Therefore the lack of positive trend could be seen as beneficial for the long-term success of the species in regards to predicted climatic changes of declining rainfall and groundwater levels (GSS 2009).

H. chrysogaster was found at sites with habitat characteristics of "high value", where sites scored highly for a high percentage of vegetation cover, stream cover and habitat diversity. More importantly, all sites with a high degree of habitat quality were positive for *H. chrysogaster* occurrence. Loss of remnant vegetation on the Swan Coastal Plain may therefore be a contributing factor to the decline in *H. chrysogaster* populations. The high percentage of vegetation and stream cover at positive sites may highlight the importance of minimizing exposure to both terrestrial and raptorial predators, as snakes and raptorial birds are known predators of young water-rats (McNally 1960). Previous studies confirm these results, where trapping success of *H. chrysogaster* was greater at water systems with offshore islands or reeds beds (Valentine *et al.* 2009), and where sites had a high percentage of riparian vegetation, shade and overhanging trees (Scott & Grant 1997).

The diet of *H. chrysogaster* is catholic, ranging from vertebrates such as fish, birds, reptiles, and mammals to invertebrates such as molluscs, crustaceans and insects (Woollard *et al.* 1978; Scott & Grant 1997; Atkinson *et al.* 2008). A diversity of habitat types within a single water system would be ideal to maximize exposure to different food items. This diversity becomes important between seasons when the species may have to switch between terrestrial and aquatic dietary items in response to changing water levels. The majority of sites with *H. chrysogaster* had greater bank angles and bank stability. This habitat selection is likely to be a response to the nesting behaviour of the species, as water-rats often burrow into river banks, creating nests at the end of tunnels (Atkinson *et al.* 2008). This therefore requires the integration of bank stability combined with a steep bank angle to prevent flooding, and possible offspring mortality, during periods of high water levels.

Although previous studies on semi-aquatic mammals have shown that predation is a detrimental and critical factor determining distribution in otherwise suitable habitats (*e.g.* Barreto *et al.* 2001), this study was limited because predation of *H. chrysogaster* could only be inferred by unexpected captures of predators such as cats, or indirect evidence. Even a small degree of predation on water-rat offspring could have a critical impact on the success of a population due to the low reproductive output compared with other rodent species such as *R. rattus*, as litter sizes range between 1–7 offspring, with 3 the average (Scott & Grant 1997). Our study was however limited by a relatively small data set, and hence we could not establish a direct link between the distribution of *H. chrysogaster* and predators.

The black rat is an introduced species held partially responsible for the extinction of many small mammal species on islands off the Western Australian coast, for example *Bettongia lesueur*, *Petrogale concinna*, *Rattus fuscipes* and *Pseudomys sp* (Morris 2002). While it is a fierce competitor with other native rodent species, a greater abundance of *R. rattus* was found at sites where *H. chrysogaster* were present. However, *R. rattus* is presumed to hold a different ecological niche to that of *H. chrysogaster*, being an opportunistic omnivore in comparison to the predominantly carnivorous and aquatic water-rat (Weir 2004). It is suggested that the two species could probably co-exist without detrimentally impacting each other (Weir 2004). However, the results

of this study show that, per trap night, *R. rattus* is more abundant where there is evidence of *H. chrysogaster*. *R. rattus* may scavenge off the feeding middens left by *H. chrysogaster*, or exhibit a preference for sites of high habitat quality also favoured by *H. chrysogaster*. However, the distribution of this commensal species is confined almost exclusively to the vicinity of human settlements and *R. rattus* is not considered a significant pest of agriculture (Taylor 1975). An extension of this study into the more rural regions of the Swan Coastal Plain may reduce the significance of this interaction.

Hydromys chrysogaster was suggested as a species critical to the persistence of functional wetland systems due to its role as a semi-aquatic predator, and as a potential bioindicator in relation to wetland habitat quality in south-western Australia (Valentine *et al.* 2009). The results presented here indicate that the core habitat requirements of *H. chrysogaster* are linked to high habitat qualities, including increased stream cover, bank stability, vegetation cover and habitat diversity. Importantly, all wetland habitats of high quality had evidence of *H. chrysogaster* presence. Although seasonality may have contributed to the low capture rates, the low number of sites with *H. chrysogaster* necessitates some degree of caution, and further studies should trap for the species outside the immediate Perth area in the south west. The impact of turbidity should also be incorporated into future studies, as water-rats hunt using visual cues under water. Our study suggests that this species may be viable as a bioindicator of wetland quality on the Swan Coastal Plain, Western Australia, although it is probably not an economic, nor rapid means of assessment due to the difficulty of implementing surveys, unless a less costly method of survey, such as motion detecting cameras, was employed.

Acknowledgements: This project was funded by a Ray Hart Memorial Scholarship and a Janice Klumpp honours grant provided by The University of Western Australia, a School of Animal Biology honours grant provided by Biota, and additional funds from the Western Australian Department of Environment and Conservation. Special thanks to Keith Morris and Brent Johnson from DEC for all the assistance provided. All work was conducted under UWA ethics permit RA/3/100/871.

References

Atkinson C A, Lund M A & Morris K D 2008 BiblioRakali: the Australian water rat, *Hydromys chrysogaster* Geoffroy, 1804 (Muridae: Hydromyinae), a subject-specific bibliography. Conservation Science Western Australia Journal 7: 65–71.

Balla S & Davis J A 1993 Wetlands of the Swan Coastal Plain Volume 5 – Managing Perth's wetlands to conserve the aquatic fauna. Water Authority of Western Australia and the Environmental Protection Authority, Western Australia.

Barreto G R, Rushton S P, Strachan R & Macdonald D W 2001 The role of habitat and mink predation in determining the status and distribution of water voles in England. Animal Conservation 1: 129–137.

Davis J A, Rosich R S, Bradley J S, Growns J E, Schmidt L G & Cheal F 1993 Wetlands of the Swan Coastal Plain (Vol. 6): Wetland Classification on the Basis of Water Quality and Invertebrate Community Data. Water Authority of Western Australia and WA Environmental Protection Authority, Perth.

Environment Australia 2001 A Directory of Important Wetlands in Australia (Third Edition). Canberra, Environment Australia.

Environmental Protection Authority (EPA) 1993 A guide to wetland management in the Perth and near Perth Swan Coastal Plain area. Bulletin 686.

Fanning F D & Dawson T J 1980 Body temperature variability in the Australian water rat, *Hydromys chrysogaster*, in air and water. Australian Journal of Zoology 28: 229–238.

Gardner J L & Serena M 1995 Observations on activity patterns, population and den characteristics of the water rat *Hydromys chrysogaster* along Badger Creek, Victoria. Australian Mammalogy 18: 71–76.

Geier A R & Best L B 1980. Habitat selection by small mammals of riparian communities: evaluating effects of habitat alterations. Journal of Wildlife Management 44(1): 16–24.

Gnangara Sustainability Strategy 2009 Interdependencies on the system (system response). Gnangara Sustainability Strategy Situation statement. Perth, Western Australia, Department of Environment & Conservation.

Harris W F 1978 An ecological study of the Australian water-rat (*Hydromys chrysogaster*: Geoffroy) in Southeast Queensland. Honours thesis, The University of Queensland.

Hill A L, Semeniuk C A, Semeniuk V & Del Marco A 1996 Wetlands of the Swan Coastal Plain, Volume 2a: Wetland mapping, classification and evaluation, main report. Water & Rivers Commission, Department of Environmental Protection, Perth, Australia.

McNally J 1960 The biology of the water rat *Hydromys chrysogaster* Geoffroy (Muridae: Hydromyinae) in Victoria. Australian Journal of Zoology 8: 170–180.

Morris K D 2002 The eradication of the black rat (*Rattus rattus*) on Barrow and adjacent islands off the north-west coast of Western Australia. *In:* Turning the tide: the eradication of invasive species; the proceedings of the International conference on eradication of island invasives (eds C Veitch & M Clout). IUCN.

Pamment D 1986 The distribution and abundance of the water rat, *Hydromys chrysogaster*, in the Coranderrk bushland and Healesville Wildlife Sanctuary, Healsville. PhD thesis, Latrobe University, Melbourne.

Scott A & Grant T 1997 Impacts of water management in the Murray-Darling Basin on the platypus (*Ornithorhynchus anatinus*) and the water rat (*Hydromys chrysogaster*). CSIRO Land & Water Technical Report 23

Shepherd K & Siemon N 1999 Planning and Management: Foreshore condition assessment in urban and semi-rural areas of south-west Western Australia. Water and Rivers Commission River Restoration Report No. RR2. Water & Rivers Commission, Perth.

Taylor K D 1975 Competitive displacement as a possible means of controlling commensal rodents on Islands. Ecological Bulletins 19: 187–194.

Triggs B 2004 Tracks, scats and other traces: a field guide to Australian mammals. Oxford University Press, South Melbourne.

Valentine L, Wilson B, Reaveley A, Huang N, Johnson B & Brown P 2009 Patterns of ground-dwelling vertebrate biodiversity in the Gnangara Sustainability Strategy study area. Department of Environment & Conservation.

Vernes K 1998 Observation of a long-range overland movement event by an adult common water rat, *Hydromys chrysogaster*. Australian Mammalogy 20: 409–410.

Weir A 2004 Australian water rat management report, Bayside City Council, Sandringham NSW 1–20

Woollard P, Vestjens W J M & Maclean L 1978 The ecology of the Eastern water rat *Hydromys Chrysogaster* at Griffith, N.S.W.: Food and Feeding Habits. Wildlife Research 5: 59–73.

Wren C D 1986 Mammals as biological monitors of environmental metal levels. Environmental Monitoring & Assessment 6: 127–144.

Landscape position predicts distribution of eucalypt feed trees for threatened black-cockatoos in the northern jarrah forest, Western Australia

E K Biggs [1], H C Finn [1], R H Taplin [2], & M C Calver [1]

[1] School of Biological Sciences & Biotechnology,
Murdoch University, Murdoch, WA 6150
✉ m.calver@murdoch.edu.au

[2] School of Accounting, Curtin University,
GPO Box U1987, Perth, WA 6845
✉ r.taplin@curtin.edu.au

Manuscript received: December 2010; accepted November 2011

Abstract

The Jarrah forest of southwestern Australia supports mineral and timber production and provides important food plants for three threatened black-cockatoo species. To assist the integration of conservation and production objectives, we studied the landscape distribution of two important black-cockatoo food sources, the eucalypts Jarrah *Eucalyptus marginata* and Marri *Corymbia calophylla*, at a mine site in the northeastern Jarrah forest in 2008. Jarrah and Marri were not distributed randomly across the landscape. Stem densities of Jarrah and Marri were highest on lower slopes and on ridgetops respectively, while stem densities for both species were lowest in lowland areas, where stems of Wandoo (*E. wandoo*) often occurred. The distribution of Jarrah and Marri 'feed trees' used by cockatoos did not follow this landscape pattern, with Marri feed trees showing a distinct association with lower slopes and lowland areas, and Jarrah feed trees more evenly distributed across landscape positions. Multiple logistic regression with biotic (stem densities), topographical (landscape position), and disturbance (*e.g.* presence of cut stumps) variables indicated that feed trees were most likely to occur on lowlands and lower slopes in the absence of Wandoo. Although Jarrah and Marri occurred at a frequency ratio of 3:1, a significantly higher proportion of Marri trees (13.0%) were used as feed trees than were Jarrah trees (5.2%). These findings suggest that Marri is likely the more important food source at a landscape-scale, but longer-term studies are needed to rule out the possibility that the relative importance of the different tree species varies seasonally and inter-annually.

Keywords: black-cockatoos, Jarrah, Marri, Jarrah forest, landscape, *Calyptorhynchus*

Introduction

Carnaby's Cockatoo *Calyptorhynchus latirostris*, Baudin's Cockatoo *C. baudinii*, and Forest Red-tailed Black-cockatoo (FRTBC) *C. banksii naso* (a subspecies) from southwestern Australia are listed as threatened species under the Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999*. All three black-cockatoos range within the region's remaining forest habitats, and two (Baudin's Cockatoos and FRTBC) feed almost exclusively on forest-based food sources (Saunders 1980; Johnstone & Storr 1998; Johnstone & Kirkby 1999, 2008). Therefore the conservation of forest feeding habitats is a priority for species recovery, particularly in the Jarrah forest, which is the region's largest forest habitat (Chapman 2007a).

Much of the Jarrah forest lies outside formal reserves, so habitat conservation requires sympathetic management and restoration practices by mining and timber production, the two major land uses within the Jarrah forest (Abbott 1998, Wardell-Johnson *et al*. 2004, Chapman 2007a, Lee *et al*. 2010). Approximately 800 000 ha of the Jarrah forest is available for timber harvesting (Conservation Commission 2004). While individual mining operations are much smaller [*e.g.*, the operations of Alcoa Alumina have affected about 13 000 ha of forest (Koch 2007)], much of the Jarrah forest is subject to mining or exploration leases under State Agreement Acts or other State legislation, allowing for on-going expansion of existing operations (RFA 1998).

Studies of crop contents and observations of feeding behaviour indicate that two eucalypt species (Jarrah *Eucalyptus marginata* and Marri *Corymbia callophylla*) are the main food sources for black-cockatoos in southwestern Western Australia forests (Saunders 1974a, 1980; Johnstone & Kirkby 1999, 2008). This reflects characteristics of their fruits and the fact that the two eucalypts are the dominant over-storey species across the extent of the Jarrah forest, occurring at a ratio of between 2:1 to 9:1 depending on location, slope position and silvicultural practices (Pryor 1959; Abbott & Loneragan 1986; Whitford 2002; Koch & Samsa 2007).

Baudin's Cockatoos are considered Marri specialists, although they also eat insect larvae, orchard fruit, and other plants (Saunders 1974b; Johnstone & Storr 1998; Cale 2003; Chapman 2007b; Johnstone & Kirkby 2008). Baudin's Cockatoos also feed on the buds and flowers of *Banksia* spp. and *Eucalyptus* spp. (Johnstone & Kirkby 2008). Marri and Jarrah seeds comprise around 90% of the diet of FRTBC, although they also feed on the seeds of

other eucalypts, as well as those of Sheoak *Allocasuarina fraseriana* and Snottygobble *Persoonia longifolia* (Robinson 1960; Johnstone & Storr 1998; Johnstone & Kirby 1999; Cooper *et al.* 2003). However, on-going research suggests that the foraging ecology of FRTBC has changed over the past 12 years, including changes in the proportions of different food plants (Ron Johnstone and Tony Kirkby, Western Australian Museum, unpublished data). Carnaby's Cockatoos also feed within forested areas, although their diet is more varied, including seeds and nectar of Jarrah, Marri, *Banksia* spp., *Hakea* spp., and *Pinus* spp. taken mainly from proteaceous scrubs and heathland, eucalypt forests and woodlands, and pine plantations (Saunders 1974a,b; Saunders 1980).

Landscape position is likely to influence where black-cockatoos feed on Jarrah and Marri within the Jarrah forest (Abbott 1998). The Jarrah forest's undulating topography is characterised by bauxitic uplands and alluvial lowlands, leading to substantial differences in soil texture, nutrient availability, and moisture content across landscape positions, and ultimately to differing vegetation types and plant productivities (Churchill 1968; Mulcahy *et al.* 1972; Havel 1975a,b; Dell *et al.* 1989). While Jarrah and Marri occur in all slope positions within the Jarrah forest, Marri is most productive in lowland areas with alluvial soils (Lane-Poole 1920, Boland *et al.* 1984), while Jarrah is often absent or rare in valleys and along drainage lines (Mattiske & Havel 1998, Havel 2000). Therefore Jarrah and Marri trees used as 'feed trees' by black-cockatoos may have predictable, and perhaps differing, distributions across landscape positions within the Jarrah forest (Abbott 1998). Patterns in the use of Jarrah and Marri trees, if present, may vary seasonally and inter-annually in response to environmental conditions and to flowering and fruiting cycles for Jarrah and Marri. Site- and landscape-scale variation may also occur because of differences in rainfall patterns and disturbances such as logging, fire history, and plant disease (Garkaklis *et al.* 2004).

We studied the foraging ecology of black-cockatoos at a mine site along the eastern margin of the northern Jarrah forest that also had a history of logging. Our objectives were to: (i) determine where in the landscape Marri and Jarrah trees and 'feed trees' occurred; (ii) assess whether landscape position, stem densities, or measures of disturbance from fire and logging best predicted the occurrence of 'feed trees'; and (iii) evaluate the implications of the findings for conserving black-cockatoo feeding habitat within areas used for timber and mineral production.

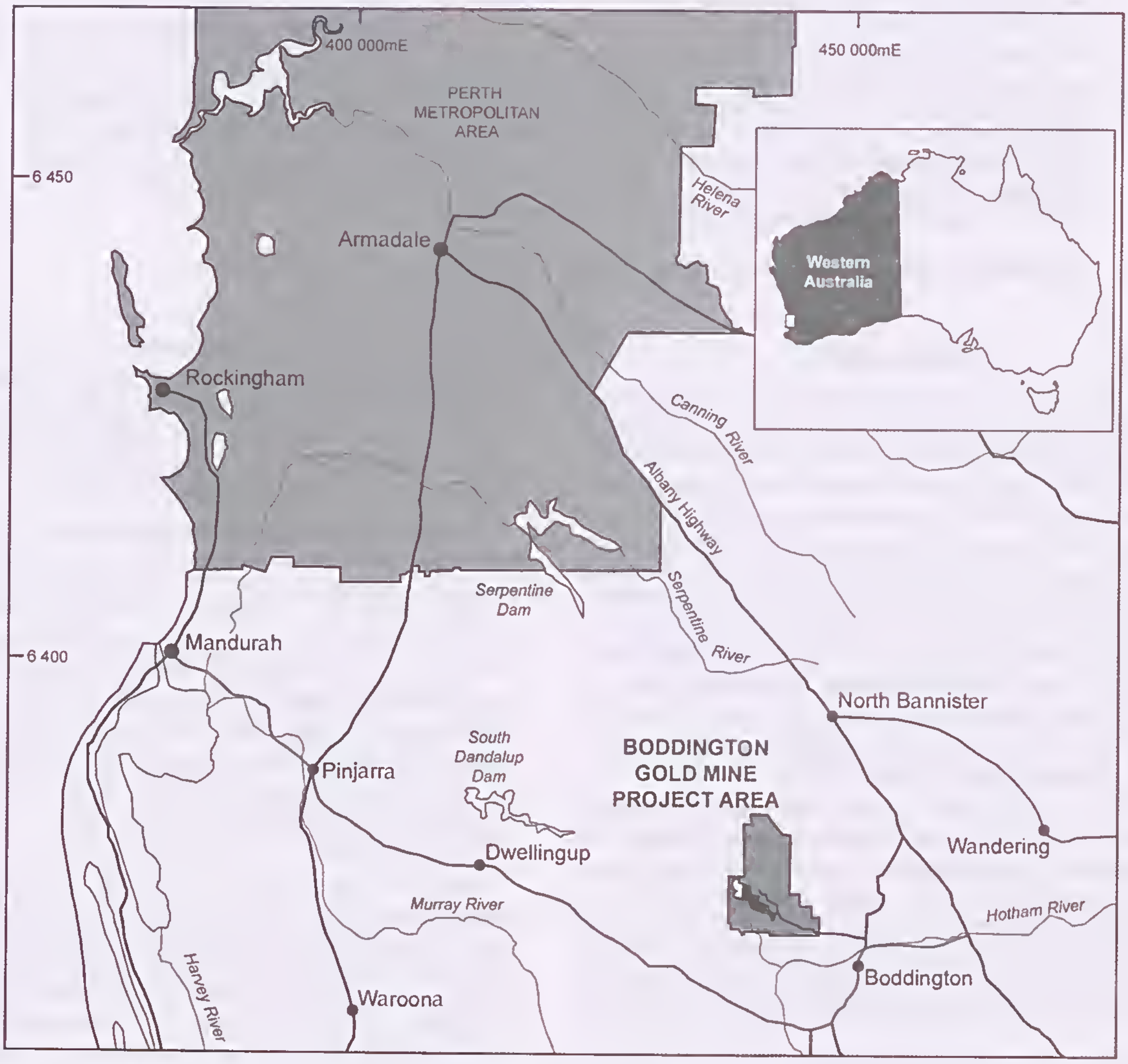


Figure 1. The location of the study site near Boddington, southwestern Australia.

Methods

Study area

The study site was located within mining tenements for Newmont Boddington Gold (NBG) (Figure 1). The NBG study site lies between the 700 mm and 800 mm isohyets on the eastern boundary of the northern Jarrah forest subregion on highly leached soils of the Darling Plateau (Dell *et al.* 1989, Rayner *et al.* 1996), near the ecotone along the eastern margin of the Jarrah forest shifting towards Wandoo woodland further east. The vegetation is mainly open eucalypt forest, with the upper-storey dominated by Jarrah interspersed with varying admixtures of Marri and Wandoo Eucalyptus wandoo, a middle-storey sometimes comprised of Bull Banksia (*Banksia grandis*) and Sheoak (*Allocasuarina fraseriana*) and a shrub layer of proteaceous and other shrubs (Dell *et al.* 1989). Sandy soils along upper slopes are associated with the presence of Sheoak and moist, fertile soils with Marri (Worsley Alumina Pty Ltd. 1999). The site was first logged in the early 1900s and has been logged at least twice since (Heberle 1997). Gold-mining operations began at the site in 1987 (Rayner *et al.* 1996).

All three black-cockatoo species were recorded within the sampling area during this study and in the course of a longer-term study from 2007–2010 (Lee *et al.* 2010; J. Lee and H. Finn, Murdoch University, unpublished data). While Carnaby's Cockatoos and FRTBC are present year-round at NBG in small numbers, larger abundances of Carnaby's Cockatoos also occur in spring and autumn as birds migrate between Wheatbelt breeding sites and feeding areas on the Swan Coastal Plain. Baudin's Cockatoos peak in abundance from April–September (J. Lee and H. Finn, Murdoch University, unpublished data). Nest sites for Carnaby's Cockatoos and FRTBC occur within or near to NBG (J. Lee and H. Finn, Murdoch University, unpublished data). NBG is considered outside the historic breeding range of Baudin's Cockatoos, with the species breeding in the Karri forest and southern Jarrah forest, although recent observations of breeding Baudin's Cockatoos in the northern Jarrah forest indicate breeding ranges may be changing (Johnstone & Kirkby 2008, 2009).

Field sampling

Six sampling locations (hereafter sites) were positioned across a diversity of landscape elements in accordance with the recommendations of Wardell-Johnson and Horwitz (1996). At each site, transect lines running parallel with the slope contour were positioned at four positions in the landscape: lowland (valley floor), lower-slope, upper-slope, and ridge-top. The transect lines varied from 420 m to 1400 m (mean transect length = 1103 m), with transect length determined by the topography of each site. Systematic plots (20 m x 20 m) were sampled at 200 m intervals along each transect (*i.e.* 0 m, 200 m, 400 m, *etc.*). Plots began at the interval point and extended for 20 m down the transect line and 10m to either side of the transect line. Plots were also established around any feed trees (recognised by the presence of feeding residues) encountered within 5 m to either side of the transect line. Thus, the basic sampling unit was a single transect located in one of four landscape elements and the plots represented sub-sampling within a transect. A further 24 plots were also sampled along transects for other purposes (*e.g.* presence of potential nest hollow).

Sampling occurred in April to July 2008. We recorded 10 variables for each plot on each occasion for use in assessing possible predictors of feeding activity: (a) landscape position (transect location: lowland, lower-slope, upper-slope or ridge-top); (b) number of woody stems [no. of woody stems >6m tall for the five dominant over- and mid-storey plants at the site: Jarrah, Marri, Wandoo, Sheoak and Bull Banksia]; and (c) four disturbance variables [presence or absence of fallen logs, cut stumps, logging track, fire scars].

Feeding residues and feed-tree plots

Different species of black-cockatoos leave characteristic markings on residues at feeding sites (Johnstone & Kirkby 1999, Cooper 2000, Cooper *et al.* 2003, Weerheim 2008), which we used to identify feed trees. We focused on the two upper-storey species Marri and Jarrah because: they are the main food plants for black-cockatoos in forest areas (with some exceptions, *e.g.* seeds and flowers of *Banksia* spp. may be critical foods at certain sites or during certain periods); their feeding residues are persistent; and they were the most abundant tree species in the area. We recorded whether Jarrah and Marri feeding residues were obviously 'old' (>1 year-old), based on colouring (*e.g.* grey, faded) and condition (*e.g.* deteriorated). FRTBC shear the base of Marri fruits at a 45º angle to remove seeds (the 'bottomslice' method), while Baudin's Cockatoos use their elongated upper mandible to pry seeds out, leaving the fruit intact (the 'lever') (Johnstone & Kirkby 1999, Cooper 2000, Cooper *et al.* 2003, Weerheim 2008).

Carnaby's Cockatoos may use either technique to feed on Marri fruit, but generally with some modification, *e.g.* the 'slicing' of fruits may occur along the side of the fruit casing (H. Finn, Murdoch University, unpublished data). The 'levering' of Marri fruits by Carnaby's Cockatoos tends to leave different marks on the fruit casings, particularly in the location of indentations by the lower mandible and in the amount of damage caused to the rim of the fruit casing. Carnaby's Cockatoos also generally feed on green Marri fruits that are soft enough for their beaks to manipulate. Observations of Carnaby's Cockatoos feeding on Marri at NBG are very infrequent (*i.e.* one observation out of more than 150 observations of Carnaby's Cockatoos at NBG between November 2007 and April 2010; J. Lee and H. Finn, Murdoch University, unpublished data). For these reasons—differences in markings on fruits and lack of observations—we attributed Marri feeding residues either to Baudin's Cockatoos or to FRTBC.

We do not consider Bull Banksia feeding residues in this study for two reasons: (1) the taking of seeds or nectar *in situ* often leaves no clear diagnostic marking on the cone or flower spike and (2) feeding marks on flower spikes (where present) becomes difficult to discern once the spikes have fallen to the ground. Likewise, Sheoak feeding residues degrade quickly, and thus were not considered. Fallen Jarrah husks degrade more quickly than do Marri husks, so the prevalence of Jarrah feeding may be underestimated. The study also could not identify the extent of feeding on insects and larvae and whether or not birds feed on the ground, in the canopy or both.

Distribution of major upper and middle-storey species

We determined if the major upper- and middle-storey species (Marri, Jarrah, Wandoo, Sheoak and Bull Banksia) were distributed evenly across the landscape elements of lowland, lower-slope, upper-slope and ridge-top using chi-squared goodness of fit tests. To avoid bias caused by over-sampling feed trees along the transects, only trees encountered in the fixed plots (*i.e.* at 200 m intervals) on each transect were included.

Distribution of Jarrah and Marri feed-trees

We used chi-squared contingency tables to test if the proportions of trees of these species actually used for feeding were associated with the species of tree and to determine if the trees of Jarrah and Marri actually fed on were distributed similarly across the four landscape elements. These analyses used data from both fixed and random plots and assumed that detection of feeding residues for the two species are similar. We do not distinguish feeding residues by black-cockatoo species for reasons of sample size and because our main objective was to identify landscape-scale patterns in the feeding activity of black-cockatoos in general.

Size and distribution of Jarrah and Marri

For each transect within each landscape element we also calculated the mean height and diameter at breast height (DBH) of the three largest Jarrah and three largest Marri trees within each plot and then used multivariate analysis of variance (MANOVA) to determine if the height and DBH of the largest Jarrah and Marri trees varied across the landscape. Prior to MANOVA, data were tested to ensure that they conformed to the assumptions of the test and any transformations required are indicated in the results.

Factors predicting the presence of feed trees

Lastly, we investigated possible predictors of whether or not a plot contained a feed tree using logistic regression, which tests the hypothesis that one or more independent variables (that may be continuous or categorical) predict the frequency of occurrence of a categorical dependent variable (see Floyd (2001) for a discussion of general principles with ecological applications). Variables measured in the 20m x 20m plots were considered as independent variables in logistic regressions as follows: (a) landscape position - three dummy variables equal to 1 if the plot is respectively on the lower slope, ridgetop or upper slope and 0 otherwise; (b) number of woody stems - the proportion of trees that were Jarrah, Marri, Wandoo, Banksia, and Sheoak; and (c) disturbance - dummy variables for the presence of cut stumps, fallen logs, fire scars, and logging tracks.

Results

Feeding residues and feed-tree plots

Jarrah and Marri feed trees were observed in 36 of 140 (25.7%) fixed-interval plots along transects. An additional 78 plots containing Jarrah and/or Marri feed trees were sampled where feed trees were encountered *ad hoc* along transects. Overall, including the 24 plots sampled for other purposes (see methods), we sampled 241 plots, of which 114 contained at least one feed-tree (*i.e.* feed-tree plots).

Most feed-tree plots contained Jarrah feed-trees (n = 26 of 36 fixed-interval feed-tree plots, 72.2%; n = 70 of 114 total feed-tree plots, 61.4%;), while less than half contained Marri feed-trees (n = 15 of 36 fixed-interval feed-tree plots, 41.7%; n = 52 of 114 feed-tree plots, 45.6%). Jarrah and Marri occurred in differing frequencies within fixed-interval plots, with Jarrah absent from 14.2% (n = 20 of 140 plots) and Marri absent from 35.7% (n = 50 of 140 plots) of fixed-interval plots. Thus, Jarrah feed-trees and Marri feed-trees occurred in 21.7% and 16.7% of fixed-interval plots in which these species were present, respectively.

We encountered 176 feed trees (Table 1), of which 54.0% (n = 95) were Jarrah and 46.0% (n = 81) were Marri. Most feed-tree plots contained only one feed-tree (n = 78 of 114 feed-tree plots, 68.4%), with similar proportions of plots containing a single Jarrah feed-tree (n = 51/70 plots, 72.9%) or a single Marri feed-tree (n = 39/52 plots, 75.0%). Eight (7.0%) feed-tree plots contained both a Marri and a Jarrah feed-tree. The number of feed trees per feed-tree plot ranged from 1 to 4 for Jarrah, and from 1 to 8 for Marri. Overall, the 241 total plots contained 1833 Jarrah stems and 622 Marri stems, a ratio of 2.95:1. The proportions of Jarrah and Marri stems that were feed trees were significantly different (Jarrah: 95/1833, 5.2% and Marri: 81/622, 13.0%; = 34.84, $p < 0.001$).

Most Marri feed-trees had feeding residues with the 'bottom-slice' markings indicative of feeding by FRTBC (n = 54 of 81 feed-trees, 66.7%), while about a third had residues with the 'levering' markings indicative of feeding by Baudin's Black-Cockatoos (n = 26 of 81 feed-trees, 66.7%). Six trees had residues with both 'bottom-slice' and 'levering' markings (n = 6 of 81 feed-trees, 7.4%). Markings were not recorded for 3 trees (n = 3 of 81 feed-trees, 3.7%). Similar proportions of Jarrah and Marri feed trees were classified as having 'old' feeding residues (Jarrah: n = 6 of 95 feed trees, 6.3%; Marri: n = 6 of 81 feed trees, 7.4%).

Distribution of major upper and middle-storey species

Significant chi-squared goodness of fit statistics based

Table 1

Number of feed trees across landscape positions, based on data from fixed plots only (n = 59 feed trees) and all plots n = 176 feed trees total).

	Ridgetop		Upper slope		Lower slope		Lowland		Total	
	Fixed	*All*	*Fixed*	*All*	*Fixed*	*All*	*Fixed*	*All*	*Fixed*	*All*
Jarrah	10	18	7	23	16	38	7	16	40	95
Marri	2	4	0	4	7	27	10	46	19	81

Table 2

The total number of woody stems >6m tall for each of the major tree species found in 20m x 20m plots at four different landscape locations. It is based on fixed-interval plots only (n = 140 fixed plots, n = 35 per landscape position), *i.e.* it excludes the extra plots located where feed trees were encountered along transects. Chi-squared values for each species are tests for equal distributions of trees across the four landscape categories. All chi-squared values are significant ($p < 0.001$).

Species	Location: Ridgetop	Upper slope	Lower slope	Lowland	Chi-squared
Jarrah	326	288	440	81	237.3
Marri	142	83	93	39	60.1
Wandoo	6	0	2	309	888.3
Bull Banksia	95	119	73	10	88.4
Sheoak	128	159	50	0	187.2

on plants scored in the fixed plots indicated that each of the five main upper- and middle-storey species was not distributed evenly across the landscape (Table 2). Jarrah was most abundant on lower slopes and least abundant in lowland. Marri was most abundant on ridgetops and also least abundant in lowland. Wandoo occurred almost exclusively in lowland. Bull Banksia and Sheoak occurred mostly on upper slopes and ridgetops, followed by lower slopes. They were scarce in lowland. The ratio of Jarrah to Marri stems increased across landscape position: ridgetop (2.3:1), upper slope (3.5:1), and lower slope (4.7:1). Within lowland areas, Wandoo, Jarrah, and Marri occurred at a ratio of 7.9:2.1:1.

Distribution of Jarrah and Marri feed-trees

Based on data from all plots, Jarrah and Marri trees used for feeding were not distributed similarly across the landscape ($\chi^2_3 = 37.8$, $p < 0.001$) (Table 1). The result is also significant if only fixed plots are considered ($\chi^2_3 = 10.2$, $p = 0.02$). Jarrah feed trees occurred predominantly on the ridgetops and lower slopes, whereas Marri feed trees were mainly on the lower slopes and in the lowlands. With lowland fixed-interval plots, a quarter of Marri stems were feed trees (n = 10 of 39 stems in fixed-interval plots, 25.6%) (Tables 1 and 2).

Size and distribution of Jarrah and Marri

Multivariate analysis of the DBH and heights of Jarrah feed trees (Wilks' lambda $_{(6,180)} = 0.95$, $p = 0.62$) and Marri feed trees (Wilks' lambda $_{(6,150)} = 0.92$, $p = 0.43$) found no significant differences in feed tree size in relation to landscape position. The situation was different, though, when the three largest trees of each species in each plot were assessed in relation to landscape position. Jarrah trees differed significantly in size across the landscape (Wilks' lambda $_{(6,678)} = 0.91$, $p < 0.001$) in height ($F_{(3,340)} = 10.2$, $p < 0.001$) but not DBH ($F_{(3,340)} = 1.5$, $p = 0.22$). Jarrah trees were taller on the upper and lower slopes and shortest in lowland plots (Table 3). The three largest Marri trees/plot also differed significantly in size across the landscape (Wilks' lambda $_{(6,386)} = 0.86$, $p < 0.001$) in height ($F_{(3,194)} = 4.1$, $p = 0.007$) and DBH ($F_{(3,194)} = 6.5$, $p < 0.001$). Marri were largest in the lowlands and on lower slopes (Table 3).

Factors predicting the presence of feed trees

Multiple logistic regression with all independent variables identified only landscape position ($p < 0.001$) and the proportion of trees that are Wandoo ($p = 0.021$) as significant predictors of feed trees. Backward elimination where insignificant variables were successively removed confirmed a final model with only these variables and this model is summarized in Table 4. Below we interpret these results, bearing in mind that the proportion of Wandoo is zero for all landscapes other than lowlands. The short duration of the study precluded any analyses of temporal patterns.

In Table 4, the first row reports the significance of landscape overall ($p < 0.001$) while the following three rows report the results for the three dummy variables for lower slope, ridgetop and upper slope. These results show that, compared to lowlands with no Wandoo, the log-odds of a feed tree are 1.2, 2.3 and 2.2 lower for the lower slope, ridgetop and upper slope respectively. Hence feed trees are most common in lowlands without Wandoo, less common on the lower slopes and least common on the ridgetops and upper slopes. For lowlands with Wandoo, the log odds decrease by 0.4 for each increase of 10% in the proportion of trees that are Wandoo. Hence the evidence suggests feed trees are more common in lowlands, but only when Wandoo is absent. When the proportion of Wandoo trees in the lowlands is

Table 3

The height and diameter-at-breast-height (dbh) across landscape positions of: (a) the three largest Jarrah and Marri trees (determined by dbh) from fixed-interval plots in different landscape elements and (b) all Jarrah and Marri feed trees encountered. Key: L = lowland, LS = lower slope, US = upper slope, R = ridge.

Position	Species	(a) 3 Largest Trees per Plot: n	dbh ± se (cm)	height ± se (m)	(b) Feed Trees: n	dbh ± se (cm)	height ± se (m)
L	Jarrah	45	41.1 ± 4.2	15.1 ± 0.8	16	64.3 ± 10.3	20.7 ± 1.0
LS		102	48.4 ± 2.0	18.8 ± 0.4	38	53.1 ± 3.7	18.6 ± 0.7
US		99	47.6 ± 1.8	18.7 ± 0.3	23	61.5 ± 4.7	20.3 ± 0.8
R		98	45.3 ± 2.1	17.5 ± 0.4	18	60.3 ± 6.2	19.6 ± 0.9
L	Marri	31	43.2 ± 4.8	15.0 ± 1.4	46	54.8 ± 4.4	18.6 ± 1.0
LS		48	33.3 ± 2.7	15.6 ± 0.9	27	50.5 ± 4.4	19.0 ± 1.2
US		54	26.4 ± 2.1	12.3 ± 0.6	4	38.8 ± 6.3	18.0 ± 1.8
R		67	26.9 ± 1.4	12.9 ± 0.5	4	32.1 ± 5.5	16.1 ± 3.8

Table 4

Summary of multiple logistic regression predicting log-odds (Exp(B)) of feed tree presence.

	B	S.E.	Wald	df	Sig.	Exp(B)
Landscape			22.381	3.0	0.000	
Lower Slope	-1.245	0.574	4.694	1.0	0.030	0.288
Ridgetop	-2.335	0.595	15.394	1.0	0.000	0.097
Upper Slope	-2.219	0.586	14.321	1.0	0.000	0.109
Wandoo	-4.147	1.062	15.258	1.0	0.000	0.016
Constant	1.755	0.519	11.412	1.0	0.001	5.781

about 50%, feed trees are about as common as they are on ridgetops and upper slopes. When more Wandoo trees are present in the lowlands, feed trees are less common there than they are on the ridgetops and upper slopes. The likelihood of feed trees on the lower slopes is higher than their likelihood in the lowlands if the proportion of Wandoo in the lowland is higher than about 30%. These results describe the current data set and some temporal variation may occur from year to year.

Discussion

Forest management in southwestern Western Australia is often focused on the retention of tree hollows for hollow-dependent fauna (*e.g.* Calver & Dell 1998, Abbott & Whitford 2002, Whitford & Williams 2002, Whitford & Stoneman 2004). While this is a vital element, it is important for management strategies to consider the full range of resources required by threatened fauna (Recher 2004). Black-cockatoos have high energetic requirements and a K-selected life history strategy, suggesting the importance of food availability for reproductive success and juvenile survivorship (Saunders 1977; Johnstone & Kirkby 1999, 2008; Cooper *et al.* 2002; Cameron 2005). This study indicates that landscape position is associated with the distribution of eucalypt feed trees for black-cockatoos, and that this association is particularly strong for Marri, with Marri feed trees concentrated on the lower slopes and in lowland areas at the study area.

Multiple logistic regression indicated that only landscape position and the proportion of trees that were Wandoo were significant predictors of where feed trees occurred, likely reflecting the tendency of Wandoo to displace competing eucalypts when present (Havel 1975a) and the predominance of Marri feed trees in lower slope and lowland plots. These findings suggest that black-cockatoos decide where to forage based upon landscape position and whether the vegetation type is a Jarrah-Marri admixture or Wandoo-dominated, and that these factors are the most robust landscape-level predictors for evaluating where high quality black-cockatoo feeding habitat is likely to occur.

This study also suggests that, at a landscape-scale, Marri may be a more important food resource for black-cockatoos than is Jarrah. While Jarrah and Marri occurred at a frequency ratio of near 3:1 within the study area, we encountered similar numbers of Jarrah (n = 95) and Marri feed trees (n = 81). In addition, a significantly higher proportion of Marri trees (13.0%) were used as feed trees than were Jarrah trees (5.2%). If further research demonstrates that this trend is robust in the face of possible annual variation, the case for a high conservation value for Marri will be strengthened.

Two factors support this conclusion about the high conservation value of Marri for black-cockatoos in the Jarrah forest. Firstly, Marri occurs at much lower abundances than Jarrah in the Jarrah forest. Whitford (2002) reports the frequency ratio of Jarrah to Marri as approximately 2:1 through the Jarrah forest, and Abbott (1998) cites unpublished forest inventory data indicating that Marri accounts for between 16% of stand basal area in the northern Jarrah forest and 33% in the southern Jarrah forest. However, the ratio of Jarrah to Marri may be as high as 9:1 in cutover forest areas (Abbott & Loneragan 1986). In this study, Jarrah stems outnumbered Marri stems by at least 2:1 in all landscape positions except for lowlands. Secondly, Marri is the primary food source for Baudin's Cockatoos, is often the principal food source for FRTBC, and is sometimes a major food for Carnaby's Cockatoo (Johnstone & Storr 1998; Saunders 1980; Abbott 1998; Johnstone & Kirkby 1999, 2008; Cale 2003; Cooper *et al.* 2003; Chapman 2007a). The value of Marri as a food source may relate in part to its energetic value, *e.g.* marri fruits are much richer in energy (7.32 kJ nut^{-1}) than are Jarrah fruits (1.24 kJ nut^{-1}) (although handling time for Marri fruits is longer) (Cooper *et al.* 2002).

No other variables considered in this study were significant predictors for black-cockatoo feed-trees. The lack of association with Marri stem densities likely relates to an increase in the productivity of Marri lower in the landscape, as suggested by the increase in DBH and tree height from ridge-tops to lowland areas. We suggest that the lack of significance for any of the disturbance variables probably reflects that these variables are indirect measures of historic (>20 years previous) logging practices, as well as the general homogeneity of stand structures within the study area. Further research is needed to address the relative habitat value of lightly-logged areas versus intensively logged areas.

While needing confirmation through broader study, the findings suggest the potential conservation value of efforts to conserve or restore lowland areas containing Marri within areas used for timber and mineral production. Bauxite mining removes laterite mantles along ridges and upper-slopes, so effects on black-cockatoo feeding habitat can be mitigated by minimising disturbance to low-lying areas where Marri feed trees are concentrated. Jarrah and Sheoak along ridgelines and mid-to-upper-slopes will be lost, but conserving large Marri may be more important in terms of reducing impacts on food availability. Historically, forestry operations have selectively removed large Marri trees for timber wood-chipping, as well as senescent trees for safety and to facilitate Jarrah growth and regeneration (Heberle 1997, Wardell-Johnson *et al.* 2004). Management prescriptions in the Forest Management Plan 2004–2013 increased the amount of Marri trees retained to provide hollows for arboreal fauna (Conservation Commission 2004). These prescriptions could be adjusted to include provisions for the retention of potential Marri feed trees and, where practical, the establishment of stand structures that facilitate the growth of larger canopy volumes. These considerations relate to Marri feed trees and we note the need for information on the landscape

distribution of black-cockatoo nest sites in order to ensure that both feeding and breeding habitat are retained.

Further research is needed in three areas. Firstly, little is known about regional variation in the distribution of eucalypt food sources for black-cockatoos. This is particularly true for the Karri *Eucalyptus diversicolor* forest, where there are no published studies on the incidence of black-cockatoo food resources and few data on the abundance and distribution of Marri. The Karri forest is the main breeding area for Baudin's Cockatoo and the availability of Marri is likely to be important for breeding success (Johnstone & Kirkby 2008). Secondly, this study focused on landscape-scale patterns in feed-tree distribution, and it remains unclear what factors influence individual feed tree selection. Studies in eastern Australia, for example, indicate that cockatoos may prefer larger trees because they provide greater protection from predators while feeding on inner branches and also reduce the number of movements required while foraging (Pepper *et al.* 2000; Maron & Lill 2004; Chapman & Paton 2005, 2006; Cameron & Cunningham 2006). Differences in fruit characteristics and productivity could also affect feed tree selection. However, while Cooper *et al.* (2003) found that FRTBC prefer Marri fruits with larger numbers of seeds and seeds of high individual weight, Weerheim (2008) found no differences in fruit morphology or seed nutrient content between Marri trees selected for feeding and trees not fed upon. Both studies did, however, observe that FRTBC return to certain trees preferentially. Phenological patterns for Marri have not been well-documented (Paap 2006), and thus it is not clear how the selection of individual trees for feeding may change over time, *e.g.* whether a tree may be fed on in years in which it fruits strongly but not in those years when it does not, and how phenology influences landscape-scale food availability. Thirdly, this study was restricted to a single year and hence did not document whether the trends described are robust within annual variation. For example, Wandoo flowers and nectar are an important food for Carnaby's Cockatoos in some years at some sites (Ron Johnstone, Western Australian Museum, unpublished data). Thus follow-up monitoring is advisable to confirm the conservation value of Marri for black cockatoos in the Jarrah forest. This monitoring would benefit from the extended observation of flocks in order to better document the use of food sources leaving feeding residues that are ephemeral or difficult to identify.

Acknowledgements: We thank Belinda Cale for drawing the figure and the personnel of Newmont Boddington Gold for their assistance. Newmont Boddington Gold provided logistical support for this research and funded a postdoctoral position for one of the authors (H. Finn). We also thank two anonymous reviewers for their comments on an earlier version of this manuscript. Ron Johnstone and Tony Kirkby explained the procedures for identifying feeding residues and gave perceptive and helpful comments on an early draft of the paper. However, they do not necessarily share our opinions or interpretations of the data.

References

Abbott I 1998 Conservation of the forest red-tailed black cockatoo, a hollow dependent species, in the eucalypt forests of Western Australia. Forest Ecology & M& Dell J 1998 Conservation status of mammals and birds in southwestern Australian forests. Is there evidence of direct links between forestry practices and species decline and extinction? Pacific Conservation Biology 4: 296–314.

Cameron M 2005 Group size and feeding rates of Glossy Black-Cockatoos in central New South Wales. Emu 105: 299–304.

Cameron M & Cunningham R B 2006 Habitat selection at multiple spatial scales by foraging Glossy Black-cockatoos. Austral Ecology 31: 597–607.

Chapman T F 2007a Forest Black Cockatoo (Baudin's cockatoo *Calyptorynchus baudinii* and Forest Red-tailed Black Cockatoo *Calyptorynchus banksii* naso) Recovery Plan. Department of Conservation & Land Management, Perth, Western Australia.

Chapman T F 2007b An endangered species that is also a pest: a case study of Baudin's Cockatoo *Calyptorhynchus baudinii* and the pome fruit industry in south-west anagement 109: 175–185.

Abbott I & Loneragan O W 1986 Ecology of Jarrah (Eucalyptus marginata) in the Northern Jarrah Forest of Western Australia. Department of Conservation & Land Management, Perth, Western Australia.

Abbott I & Whitford K 2002. Conservation of vertebrate fauna using hollows in forests of south-west Western Australia: strategic risk assessment in relation to ecology, policy, planning, and operations management. Pacific Conservation Biology 7: 240–255.

Boland D J, Brooker M I H, Chippendale G M, Hall N, Hyland B P M, Johnston R D, Kleinig D A & Turner J D 1984 Forest trees of Australia. Nelson-CSIRO, Melbourne, Victoria.

Cale B 2003 Carnaby's Black-Cockatoo (*Calyptorhychus latirostris*) Recovery Plan 2002–2012. Department of Conservation & Land Management, Perth, Western Australia.

Calver M C Western Australia. Journal of the Royal Society of Western Australia 90: 33–40.

Chapman T F & Paton D C 2005 The Glossy Black-cockatoo (*Calyptorhynchus lathami halmaturinas*) spends little time and energy foraging on Kangaroo Island, South Australia. Australian Journal of Zoology 53: 177–183.

Chapman T F & Paton D C 2006 Aspects of Drooping Sheoaks (*Allocasuarina verticillata*) that influence Glossy Black Cockatoo (*Calyptorhynchus lathami halmaturinas*) foraging on Kangaroo Island. Emu 106: 163–168.

Churchill D M 1968 The distribution and prehistory of *Eucalypt diversicolor* F. Muell., *E. marginata* Donn ex Sm., and *E. calophylla* R. Br. in relation to rainfall. Australian Journal of Botany 16: 125–151.

Conservation Commission of Western Australia 2004 Forest Management Plan 2004–2013. Conservation Commission of Western Australia, Perth, WA.

Cooper C 2000 Food manipulation by southwest Australian cockatoos. Eclectus 8: 3–9.

Cooper C E, Withers P C, Mawson P R, Johnstone R, Kirkby T, Prince J, Bradshaw S D, & Robertson H 2003 Characteristics of Marri (*Corymbia callophylla*) fruits in relation to the foraging behaviour of the Forest Red-tailed Black Cockatoo (*Calyptorhynchus banksii naso*). Journal of the Royal Society of Western Australia 86: 139–142.

Cooper C E, Withers P C, Mawson P R, Bradshaw S D, Prince J & Robertson H 2002 Metabolic ecology of cockatoos in the south-west of Western Australia. Australian Journal of Zoology 50: 67–76.

Dell B, Havel J J & Malajczuk N (eds.) 1989 The Jarrah Forest: A Complex Mediterranean Ecosytem. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Floyd R 2001 Logit modelling and logistic regression: aphids, ants and plants. *In*: Design and Analysis of Ecological Experiments (eds S M Scheiner & J Gurevitch). Oxford University Press, Oxford, UK, 197–216.

Garkaklis M J, Calver, M C, Wilson, B A & Hardy G E St J 2004 Habitat alteration caused by an introduced plant disease, *Phytophthora cinnamomi*: a potential threat to the conservation of Australian forest fauna. *In*: Conservation of Australia's

Forest Fauna (2nd edition) (ed D Lunney). Royal Zoological Society of NSW, Sydney, NSW, 899–913.

Havel J J 1975a Site vegetation mapping in the northern jarrah forest (Darling Range) I. Definition of site vegetation types. Forests Department Western Australia, Bulletin 86, Perth, Western Australia.

Havel J J 1975b Site vegetation mapping in the northern jarrah forest (Darling Range) II. Location and mapping of site vegetation types. Forests Department Western Australia, Bulletin 87, Perth, Western Australia.

Havel, J J 2000. Ecology of the Forests of South-western Australia in Relation to Climate and Landforms. Ph.D. thesis, Murdoch University, Perth, WA.

Heberle G 1997 Timber harvesting of Crown land in the south-west of Western Australia: an historical review with maps. CALM Science 2: 203–224.

Johnstone R E & Kirkby T 1999 Food of the Forest Red-tailed Black Cockatoo *Calyptorynchus banksii naso* in south-west Western Australia. Western Australian Naturalist 22: 167–177.

Johnstone R E & Kirkby T 2008 Distribution, status, social organisation, movements and conservation of Baudin's Cockatoo (*Calyptorhynchus baudinii*) in South-west Western Australia. Records of the Western Australian Museum. 25: 107–118.

Johnstone R E & Kirkby T 2009 Birds of the Wungong Dam catchment, Bedfordale, Western Australia. Western Australian Naturalist 26: 219–274.

Johnstone R E & Storr G M 1998 Handbook of Western Australian Birds. Volume I – Non-passerines (Emu to Dollarbird). Western Australian Museum, Perth, Western Australia.

Koch J M 2007 Alcoa's mining and restoration process in south western Australia. Restoration Ecology 15: 11–16.

Koch J M & Samsa G P 2007 Restoring Jarrah forest trees after bauxite mining in Western Australia. Restoration Ecology 15 (Supplement): S17–S25.

Lane-Poole C E 1920 Statement Prepared for the British Empire Forestry Conference, London, 1920. Government Printer, Perth, Western Australia.

Lee J, Finn H & Calver M C 2010 Post-mining vegetation provides feeding habitat for threatened black-cockatoos within eight years. Ecological Management and Restoration 11: 141–143.

Maron M & Lill A 2004 Discrimination among potential buloke (*Allocasuarina luehmannii*) feeding trees by the endangered south-eastern red-tailed black-cockatoo (*Calyptorhynchus banksii graptogyne*). Wildlife Research 31: 311–317.

Mattiske E M & Havel J J 1998 Regional Forest Agreement, Vegetation Complexes, Perth Western Australia. Western Australia Department of Conservation and Land Management, Perth, Western Australia and Department of Environment and Heritage, Canberra, Australian Commonwealth Territory.

Mulcahy M J, Churchward H M & Dimock G M 1972 Land form and soils on an uplifted peneplain in the Darling range, Western Australia. Australian Journal of Soil Research 10: 1–14.

Paap T 2006 The Incidence, Severity and Possible Causes of Canker Disease of *Corymbia calophylla* (Marri) in the Southwest of Western Australia. Unpublished PhD thesis, Murdoch University, Perth, Western Australia.

Pepper J W, Male T D & Roberts G E 2000 Foraging ecology of the South Australian glossy black-cockatoo (*Calyptorhynchus lathami halmaturinus*). Austral Ecology 25: 16–24.

Pryor L D 1959 Species distribution and association in *Eucalyptus*. Monographiae Biologicae 8: 461–471.

Rayner G A, Scott P R & Piper R J 1996 Environmental management at the Boddington Gold Mine—an operation in a multiple land use catchment. In: Environmental Management in the Australian Minerals and Energy Industries (ed D R Mulligan). University of New South Wales Press, Sydney, New South Wales, 348–363.

Recher H F 2004 Eucalypt forest birds: the role of nesting and forging resources in conservation and management. In: Conservation of Australia's Forest Fauna (2nd edition) (ed by D Lunney). Royal Zoological Society of New South Wales, Sydney, New South Wales, 23–35.

RFA 1998 Assessment of Mineral and Hydrocarbon Resources in the South-west Forest Region of Western Australia. Joint Commonwealth and Western Australian Regional Forest Agreement Steering Committee.

Robinson A 1960 The importance of Marri as a food source to south-western Australian birds. The Western Australian Naturalist 7: 109–115.

Saunders D A 1974a The occurrence of the white-tailed black cockatoo, *Calyptorhynchus baudinii*, in *Pinus* plantations in Western Australia. Australian Wildlife Research 1: 45–54.

Saunders D A 1974b Subspeciation in the White-tailed Black Cockatoo, *Calyptorhynchus baudinii*, in Western Australia. Australian Wildlife Research 1: 55–69.

Saunders D A 1977 The effect of agricultural clearing on the breeding success of the White-tailed Black Cockatoo. Emu 77: 180–84.

Saunders D A 1980 Food and movements of the short-billed form of the White-tailed Black Cockatoo. Australian Wildlife Research 7: 257–69.

Wardell-Johnson G & Horwitz P 1996 Conserving biodiversity and the recognition of heterogeneity in ancient landscapes: a case study from south-western Australia. Forest Ecology and Management 85: 219–238.

Wardell-Johnson G, Calver M C, Saunders D A, Conroy S & Jones B A 2004 Why the integration of demographic and site-based studies of disturbance is essential for the conservation of jarrah forest fauna. *In*: Conservation of Australia's Forest Fauna (2nd edition) (ed fsD Lunney). Royal Zoological Society of New South Wales, Sydney, New South Wales, 394–417.

Weerheim M S 2008 Distribution Patterns and Habitat use of Black Cockatoos (*Calyptorhynchus* spp) in Modified Landscapes in the South-west of Western Australia. MSc thesis, Edith Cowan University, Perth, Western Australia.

Whitford K R 2002 Hollows in jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) trees I: hollow sizes, tree attributes and ages. Forest Ecology and Management 160: 201–214.

Whitford K R & Williams M R 2002 Hollows in jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) trees II. Selecting trees to retain for hollow dependent fauna. Forest Ecology and Management 160: 215 – 232.

Whitford K and Stoneman G 2004 Management of tree hollows in the jarrah *Eucalyptus marginata* forest of Western Australia. In: Conservation of Australia's Forest Fauna (2nd edition) (ed by D Lunney). Royal Zoological Society of New South Wales, Sydney, New South Wales, 807–829.

Worsley Alumina Pty. Ltd. 1999 Worsley Alumina Boddington Gold Mine Project. Flora and Fauna Studies. Worsley Alumina Pty. Ltd., Perth, Western Australia.

Aquatic invertebrates of rockholes in the south-east of Western Australia

I A E Bayly [1,2], S A Halse [3] & B V Timms [4]

[1] School of Biological Sciences, Monash University, Melbourne, Vic., 3800

[2] Address for correspondence: 501 Killiecrankie Road, Killiecrankie, Flinders Island, Tas., 7255
✉ iaebayly@activ8.net.au

[3] Bennelongia Pty Ltd, 5 Bishop Street, Jolimont, WA, 6014
✉ stuart.halse@bennelongia.com.au

[4] Australian Wetlands & Rivers Centre, University of NSW, Kensington, NSW, 2052
✉ brian.timms@unsw.edu.au

Manuscript received March 2011; accepted October 2011

Abstract

Twelve flooded rockholes located to the east of the Yilgarn Craton, in the Western Australian sector of the Great Victoria Desert, were sampled for aquatic invertebrates. The fauna was depauperate in comparison with that of pan gnammas on the Yilgarn Craton. Only three crustacean species (*Lynceus* sp. nov., *Moina australiensis* and *Sarscypridopsis* sp. nov.) and one insect family (Culicidae) occurred in more than half of the rockholes. Although deep rockholes like pit and pipe gnammas typically have a longer hydroperiod than pan gnammas they have few, mainly eurytopic, species.

Keywords: Great Victoria Desert, Officer Basin, rock pool, gnamma, *Lynceus, Moina australiensis, Sarscypridopsis*, Culicidae

Introduction

If we consider that part of Western Australia south of latitude 26°S, it consists of two major geological regions: that to the west of longitude 123° 30'E (say west of Yamarna) is occupied mainly by the Yilgarn Craton consisting chiefly of Achaean granites, and that to the east of this line (the Eucla and Officer Basins) of largely non-granite rocks of lesser age (Fig. 1). Much of the latter region was subject to extensive marine inundation in the Early Cretaceous around 120–100 Ma BP and a lesser marine flooding in the Eocene from about 52–37 Ma BP (BMR Palaeo-geographic Group 1990), but most of the Yilgarn Craton escaped these floodings. The Yilgarn region is studded with hundreds of granite inselbergs on the surface of which chemical weathering has etched out thousands of gnammas or rockholes. Either intermittently or episodically these gnammas are filled with rainwater and provide habitat for a surprisingly diverse assemblage of aquatic invertebrates. The nature of this assemblage for the Yilgarn region has received considerable attention during the past two decades and is now relatively well known (see, *e.g.*, Bayly 1997; Pinder *et al.* 2000; Timms 2006; Jocqué *et al.* 2007). In contrast, the aquatic fauna of rockholes in the south-east of Western Australia, those to the east of the Yamarna-Balladonia line, has been almost totally neglected.

The word "gnamma" comes from the Nyungar language and refers to a rockhole, especially one capable of holding water, and is now firmly established in the anthropological, biological and geological literature. Following the seminal paper of Twidale & Corbin (1963) a gnamma is a rockhole that has been produced by chemical weathering. Despite the fact that chemical weathering is generally more potent than physical weathering (Twidale & Campbell 2005), some rockholes are formed wholly or mainly by physical processes such as thermal expansion, frost riving, growth of crystals or pressure release. Such processes commonly result in the shattering of rocks. Silcock (2009) treats rockholes in the sandstone ranges of the Lake Eyre Basin as the product of fracturing followed by the scouring out of rock fragments by running water. Rockholes produced by physical processes generally have sharp, angular surfaces in contrast to the more smoothly rounded features that are so characteristic of true gnammas. While most of the rockholes encountered in this study are gnammas in the sense of Twidale and Corbin, albeit of the non-granite variety, some are not because they were judged as being produced mainly by physical processes. In summary, all gnammas are rockholes but not all rockholes are gnammas. A further point is that most deep gnammas on non-granite substrata such as the laterites that dominate the so-called "breakaway" country in Western Australia are morphologically quite different from those on granite. Unlike the pit gnammas on granite, almost all of which are basin-shaped, many of the deep non-granite gnammas are tube-like or cylindrical with vertical sides and flat bottoms. Timms (in manuscript) has distinguished these by the new name "pipe gnammas". This new term applies to a subset of what, in more general terms, may be called "cylindrical gnammas".

Also included in this study are two rather squarish, rock-floored basins surrounded by rock on three sides but dammed by a ridge of soft sediments on the fourth. These may be plunge pools of systems that are intermittently lotic after occasional heavy rain (but this is not certain) and are referred to as "waterholes" rather than "rockholes" in Table 1, but the title and text of

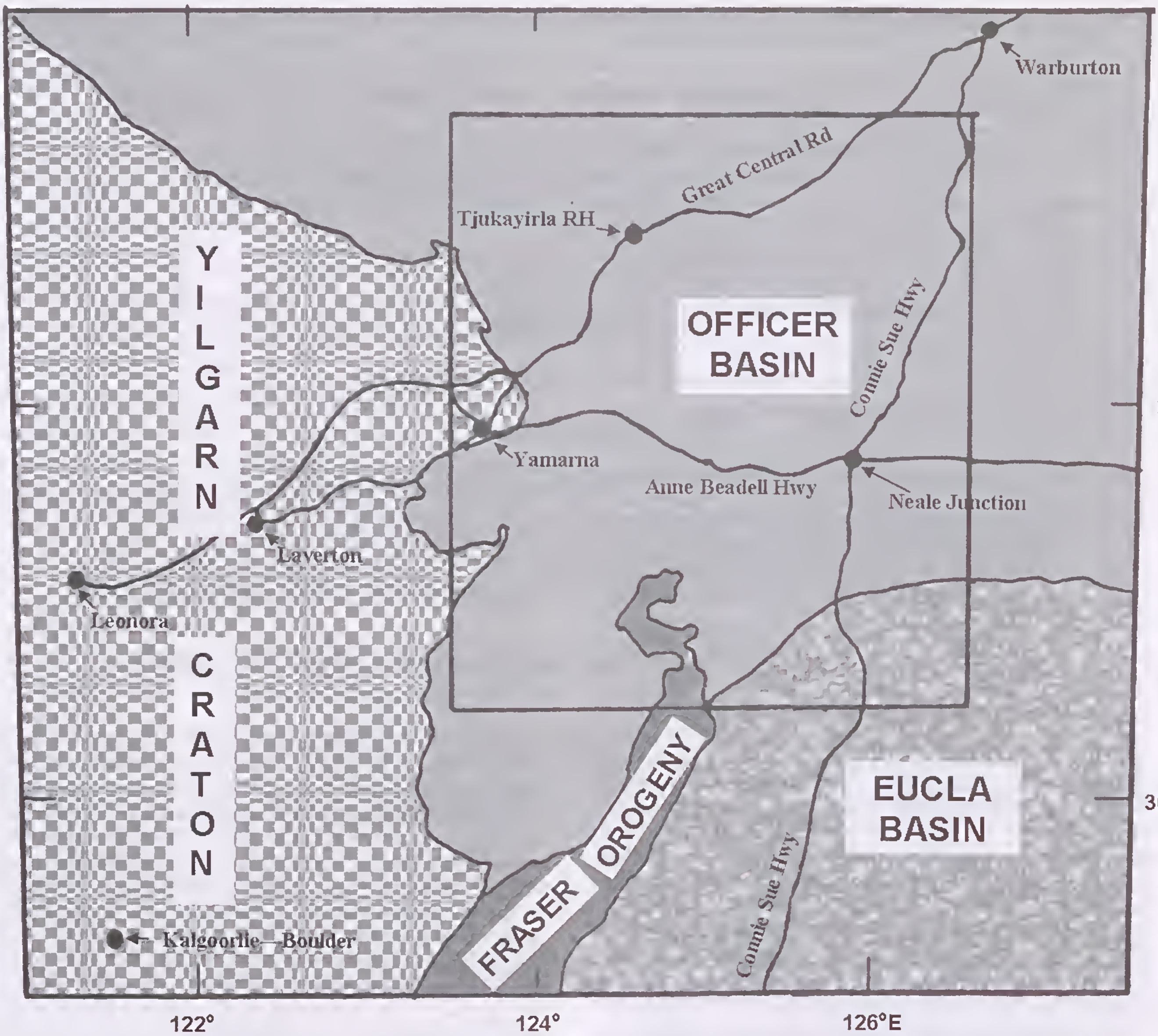


Figure 1. The study area (inset) in relation to the major geological elements surrounding it.

this paper has not been accordingly encumbered with dual terminology. The labelling of these two basins as waterholes is concordant with Silcock's (2009) contention that, in general, true rockholes are not located on major drainage lines (potholes gouged into hard bedrock forming the channel of major but ephemeral rivers would, of course, be an exception).

The aim of this paper is to provide inaugural data on the invertebrate assemblages of rockholes in the Officer Basin, and to make tentative comparisons with the better known Yilgarn region.

Study Areas

All rockholes selected for study lie outside the Yilgarn Craton, to the east of longitude 124° E (Figs 1 & 2). One collection of zooplankton from a rockhole near Bartlett Bluff to the south-east of Lake Rason was made by Ian Elliot on 6 July 2010. All other collections and field measurements were carried out by one of us (IAEB) during an expedition into the Great Victoria Desert, largely following the route taken by Frank Hann in 1903 (see Donaldson & Elliot 1998), between 24 August and 5 September 2010. All of the Hann Track localities lie easily within the Officer Basin which is dominated by Permian rocks (Myers & Hocking 1998). The Bartlett Bluff rockhole lies very close to the boundary between the Fraser Orogeny and a small pocket of the Officer Basin. Beard (2002) treats the Great Victoria Desert as being situated on the Gunbarrel Basin which overlies the Officer Basin, but the former basin is not recognized in South Australia, so the latter is adopted in this paper. Rainfall registrations (mm) at Laverton (nearest available station) for the seven months preceding sampling in 2010 were as follows (long term monthly means in parentheses): January 12.0 (24.0), February 8.4 (29.8), March 5.4 (30.1), April 38.0 (23.0), May 17.4 (23.5), June 8.8 (23.8), July 24.4 (16.5), January–July 114.4 (170.7). Only 2.0 mm fell in August as against the long term average of 13.3 mm.

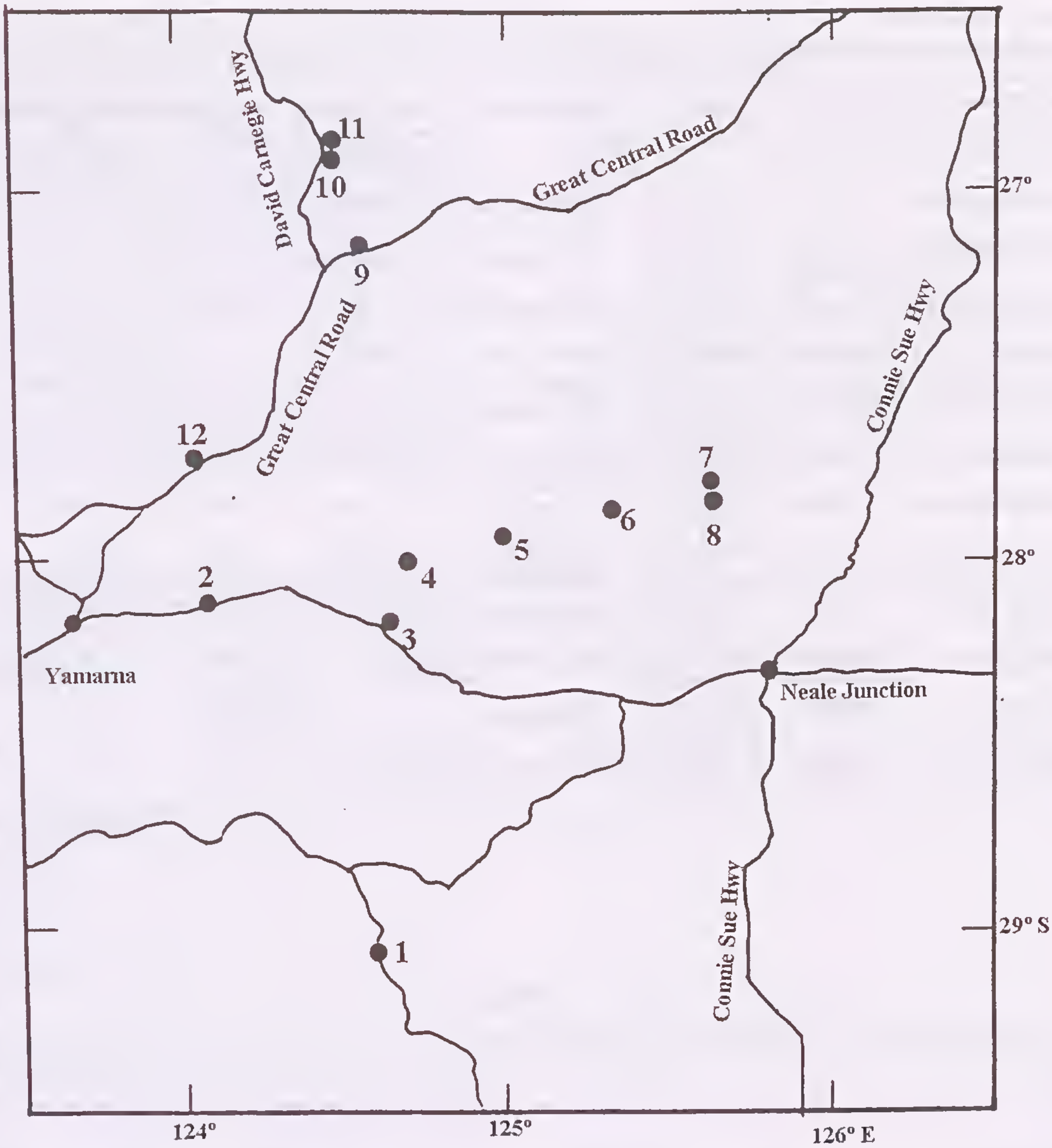


Figure 2. Details of the study area showing the location of water-containing rockholes sampled for invertebrates. 1, Bartlett Bluff Rockhole; 2, Point Sunday Rockhole; 3, Knight Gnamma Holes; 4, Lily Rockhole; 5, Sunday Surprise Rocks; 6, Amy Waterhole; 7, Saunders Range North; 8, Point Saunders Waterhole; 9, Tugaila Rockhole; 10, Pikalu Rockholes; 11, Calcalli Rockhole; 12, Eurothurra Rockhole.

Methods

Invertebrates were collected via a net with a rectangular frame measuring 20 x 30 cm to which was attached nylon mesh with an aperture size of 150 µm. The net was operated so as to explore all major parts of the hydro-space without, however, deliberately taking up bottom sediment. The catch was preserved in 80% ethanol. At locality 4 (Lily Rockhole) only, a small phytoplankton net with mesh aperture of 30 µm was deployed to collect phytoplankton, and invertebrates of rotifer or protozoan size. This catch was preserved in Lugols solution.

In the laboratory, initial sorting of specimens into major groups was carried out (by IAEB) under a stereo-microscope. Ostracods were identified by Halse, and large branchiopods and cladocerans by Timms. Other taxa were identified by Bayly.

At each rockhole sampled during the Hann Track expedition, the maximum length and maximum width (measured at right angles to the maximum length) at the water surface, and maximum water depth, were recorded using a flexible steel measuring tape. Water temperature and conductivity (K 25) were measured *in situ* with a YSI EC300 portable conductivity-temperature meter. Approximate total dissolved solid (TDS) values, as a colligative property of conductivity, were also recorded. No conductivity measurement was made at Bartlett Bluff rockhole.

Results

Physical dimensions of the rockholes, and conductivity and TDS data for the water they contained, are presented in Table 1. Apart from Lily Rockhole and the two presumptive plunge pools, the rockholes were small, with

Table 1

Geographical, physical and chemical features of small aquatic habitats in the Great Victoria Desert sampled for invertebrates.

Locality no. & name	Date	Lat. & long.	Type of hole	Max. length X max. width or diameter (cm)	Max. water depth (cm)	Conductivity (K25) (mScm-1)	Putative TDS (mg L-1)
(1) Bartlett Bluff Rockhole	6.vii.2010	29°04.900'S 124°36.615'E	Non-gnamma rockhole	100 X 50	50		
(2) Point Sunday Rockhole	24.viii.2010	28°07.433'S 124°03.077'E	Pipe gnamma	80	30	165	107
(3) Knight Gnamma Holes	25.viii.2010	28°12.795'S 124°39.993'E	Pipe gnamma	54	28	1028	668
(4) Lily Rockhole	26.viii.2010	28°00.271S 124°44.832'E	Non-gnamma rockhole	400 X 310	83	155	101
(5) Sunday Surprise Rocks	27.viii.2010	27°57.369'S 125°00.350'E	Pipe gnamma	20	13	214	139
(6) Amy Waterhole	27.viii.2010	27°52.097S 125°18.553'E	Plunge-pool waterhole	400 X 300	52	45	29
(7) Saunders Range North	29.viii.2010	27°49.693'S 125°37.453'E	Pipe gnamma	83 X 56	42	179	117
(8) Pt Saunders Waterhole	30.viii.2010	27°50.865'S 125°38.356'E	Plunge-pool waterhole	255 X 220	37	69	45
(9) Tugaila Rockholes	3.ix.2010	27°09.355'S 124°34.378'E	Pipe gnamma	100	51	14	9
(10) Pikalu Rockholes	4.ix.2010	26°54.795'S 124°27.505'E	Pipe gnamma	80	96	86	56
(11) Calcalli Rockhole	4.ix.2010	26°54.007'S 124°28.070'E	Pipe gnamma	60	78	64	42
(12) Eurothurra Rockhole	5.ix.2010	27°44.786'S 124°03.016'E	Pipe gnamma	120 X 120	66	137	89

Table 2

Occurrence of inverterbrate taxa in rockholes in the Great Victoria Dessert

Locality	1	2	3	4	5	6	7	8	9	10	11	12
Taxa												
CRUSTACEA												
Laevicaudata												
Lynceus sp. nov.	X	X		X		X	X	X	X	X		X
Lynceus macleayanus (King)			X		X							
Lynceus sp.											X*	
Cladocera												
Alona sp				X								
Ceriodaphnia dubia Richard				X								
Chydorus sp				X								
Moina australiensis Sars	X			X	X	X	X	X	X	X		X
Ostracoda												
Heterocypris tatei Brady			X		X		X		X			
Heterocypris sp.	X											
Ilyodromus sp.				X								
Sarscypridopsis sp. nov.	X	X		X	X	X	X		X	X		X
INSECTA												
Chironomidae							X	X				
Culicidae	X	X		X			X	X	X		X	
Other Diptera	X				X		X	X	X		X	
Zygoptera						X						
Total no. taxa	6	3	2	8	5	4	7	5	6	3	3	3

*Based on an abundance of distinctive metanauplii.

openings in the range 20–120 cm. All water depths were less than 1.0 m. Conductivities (K25) ranged from 14–1028 μS cm^{-1}, and TDS values from 9–668 mg L^{-1}, which data indicate fresh water in all cases.

The results of taxonomic studies are presented in Table 2. A total of 14 taxa were recorded, but if locality 4 is excluded, the total is reduced to only 10. It was a simple assemblage: the pea shrimp, *Lynceus*, occurred in all rockholes, and *Moina australiensis*, *Sarscypridopsis* sp. nov. and culicid larvae in most. Other important taxa were *Heterocypris tatei* and dipteran larvae other than those of Culicidae and Chironomidae.

Table 3 compares present findings with those for different types of depression on Yilgarn granite. It is convenient to restrict this comparison to Crustacea. The Officer Basin series aligns closely with granite pit gnammas but not with data from Yilgarnia that includes pan gnammas. *Lynceus, Moina australiensis* and *Heterocypris* are distinctive taxa for rockholes that are not pans. Table 3 also shows that the shallow pans are considerably more speciose than deeper depressions whether they are granite pits or non-granite pipe gnammas.

Discussion

A striking feature of this series of rockholes is the depauperate nature of the invertebrate fauna, with the total number of taxa per locality lying in the range 2–8 (mean 4.6) (Table 2). Further taxonomic resolution of insect taxa and repeated sampling at times other than late-winter/early-spring would doubtless elevate this

Table 3

Comparison of crustacean taxa from different types of rockholes and different regions. (The data sets were compiled on different bases with respect to sampling intensity, seasonal coverage and geographical coverage.)

Region and cavity type	Officer Basin non-granite rockholes	Yilgarn granite pit gnammas	Yilgarn granite pan gnammas	Yilgarn granite pan and pit gnammas	Yilgarn granite pan gnammas
Study	**Present**	**Timms (unpublished)**	**Bayly (1997)a**	**Pinder *et al.* (2000)**	**Jocqué *et al.* (2007)**
Some commonly found taxa					
LAEVICAUDATA					
Lynceus macleayanus	X	X		Xd	
Lynceus sp. nov.	X				
SPINICAUDATA					
Caenestheriella mariae			Xb	Xe	X
Limnadia badia			Xc	Xf	X
ANOSTRACA					
Branchinella longirostris			X	X	X
CLADOCERA					
Daphnia carinata		X			
Daphnia jollyi			X	X	
Ephemeroporus			X	X	X
Macrothrix breviseta			X	X	X
Macrothrix hardingi		X	X	X	X
Moina australiensis	X	X			
Neothrix armata			X	X	X
Planicirculus alticarinatus			X	X	X
OSTRACODA					
Bennelongia barangaroo			X	X	X
Candonocypris			X	X	X
Cypretta baylyi			X	X	X
Cypricercus		X			
Heterocypris tatei	X	X			
Heterocypris sp.		X			
Ilyodromus amplicolis			X	X	X
Limnocythere			X	X	X
Sarscypridopsis			X	X	X
Sarscypridopsis sp. nov.	X				
COPEPODA					
Boeckella opaqua			X	X	X
Boeckella triarticulata		X			
Total crustacean taxa	**10**	**12+**	**60**	**90**	**29**

a, omitting data for one pit gnamma and one pan gnamma almost (intermittently) connected to a deep artificial impoundment; b, reported as *Cyzicus* sp.; c, as *Limnadia* sp.; d, present in one pit gnamma only; e, as *Cyzicus* sp.; f, as *Limnadia* sp.

number, but is judged unlikely to alter the interim assessment that the fauna is depauperate. In contrast, Jocqué *et al.* (2007), sampling in winter only, obtained a mean value of 18.7 invertebrate taxa per pool for a series of 57 pools on Hyden Rock which is located on the Yilgarn Craton and consists of granite. It is not possible to extract data on taxa per rockhole from the study of Pinder *et al.* (2000), but if Protozoa and Rotifera (not generally included in the present study) are excluded, they obtained a mean number of 44 species per granite outcrop on the Yilgarn Craton (approximately 10 pools per outcrop were sampled).

The fauna of locality 4, Lily Rockhole, was exceptional in including three species of Cladocera, and one of Ostracoda, that occurred at no other locality (they were all taken with the 150 μm net). This higher diversity of micro-crustaceans is almost certainly related to the abundance of macrophytes in this rockhole and the fact that it represents a semi-permanent aquatic habitat. A separate study of this rockhole and its plants (I. Bayly, unpublished) established that it experiences exceptionally long hydroperiods for a desert locality, and contains an abundance of *Ottelia ovalifolia* and *Potamogeton octandrus*. Collections from this locality with a phytoplankton net contained large numbers of the protozoan *Euglypha*. It is thought that this testate amoeba is associated with the undersurface of the floating leaves, and the submerged leaves and stems, of the two macrophyte species. The elevated species richness in Lily Rockhole suggests that lack of habitat heterogeneity in the remaining 11 rockholes may be a significant factor in their paucity of species.

Data presented in Table 3 suggest that the morphology of rockholes may have a major influence on their aquatic biology, with the deeper holes, containing water of greater permanency, being less speciose. At first sight this runs completely counter to current orthodoxy regarding the relationship between hydroperiod and the degree of complexity of community structure. Wellborn *et al.* (1996) explored the concept of what they called "permanency gradient" and "permanency transition", noting that "as hydroperiod increases, so does the potential species pool", and quoting several studies that observed positive correlations between degree of permanence and species richness. Concordantly, Therriault & Kolasa (2001) found that biotic diversity in coastal rock pools decreases with decreasing hydroperiod, and this general principle was endorsed by Jocqué *et al.* (2010). Finally, the data in Table 3 apparently run counter to Bayly's (1997) demonstration that in pan gnammas there is a significant positive correlation between species richness and water volume. Present findings are, therefore, difficult to explain without the realization that pit (or pipe) and pan gnammas are not as closely comparable as habitats as hitherto thought, and have few common species (Table 3). The two habitats present different levels of stress apart from hydroperiod. Pit gnammas are rather "generalized" habitats with relatively long hydroperiods and mainly eurytopic species, whereas pan gnammas are more "specialized" habitats which not only require a life cycle attuned to short hydroperiods, but also special adaptations to the short, highly transparent water column. Dark pigments to protect against strong UV radiation may be cited as an example of the latter. Pans have been subject to prolific speciation, perhaps as a result of marked climate changes over long periods of geological time, resulting in multiple species in many genera, particularly of Cladocera and Ostracoda (Pinder *et al.* 2000). Their crustacean-dominated fauna is specialized and largely endemic. In both the shallow and deep pools there is increasing species richness with increasing water volume (*e.g.* Bayly 1997 for pans; B. Timms unpublished for pits) but it is not appropriate to amalgamate the two sets of data.

Two marine intrusions into what is now the Officer Basin would have caused mass annihilation of freshwater habitats. The first of these occurred in the Early Cretaceous about 120–110 Ma BP, and the second in the Eocene somewhere in the range 52–37 Ma BP (BMR Palaeogeographic Group 1990). Iasky (1990) confirmed that the last marine transgression into parts of the Officer Basin, as represented by the Lampe Formation, occurred in the Eocene. [The Eucla Basin was again flooded by marine waters in the Early Miocene.] With the final retreat of marine waters from the Officer Basin occurring early in the Tertiary much time has elapsed for dispersal from the Yilgarn region and elsewhere to the Officer Basin. The availability of long stretches of time is a key consideration because, after many decades of untested assumptions and myths to the contrary, it is now recognized that dispersal in passively dispersed freshwater invertebrates is a very infrequent event (see Bohanak & Jenkins 2003 for masterly review). Good direct and experimental evidence of poor powers of dispersal in freshwater zooplankton including micro-crustaceans is provided by Jenkins (1995) and Jenkins & Underwood (1998). As for macro-crustaceans, Hulsmans *et al.* (2007) reviewed the evidence from several studies on anostracans and concluded that there is "high genetic differentiation on a scale of more than 100 m". In their own study of *Branchipodopsis wolfi* they found that a distance of 50 m is already an effective barrier to gene flow and that such small distances are a constraint on effective dispersal. Jocqué *et al.* (2010) point out that rock pools are a repository for a remarkably high diversity of passive dispersers, and that the diversity of rock pool species in Australia apparently exceeds that of all other continents.

Green *et al.* (2008) considered the potential of water birds as dispersers of invertebrates in the desert regions of Australia. However, the rockholes of the present study have a small surface area, and in some cases cryptic entrances as a result of overarching vegetation, and, if an anthropocentricism is permissible, they appear unlikely to attract the attention of large water birds such as the four species (Grey Teal, Eurasian Coot, Black Swan and Australian Pelican) studied by Green *et al.* (2008).

The most widely distributed insect group in the present study, the Culicidae, is one of the very few actively dispersed taxa for which the extent of dispersal has been accurately quantified. Service (1997) emphasized that short distance dispersal is the norm in mosquito biology; using capture-mark-recapture methods he showed that the maximum distance flown is usually in the range 1–5 km, with almost half the records being less than 1 km. One overseas rock pool species, *Aedes vittatus*, is not only an active disperser but also has desiccation-resistant eggs (Roberts 2004).

Insects such as hemipterans and coleopterans, that are common in Yilgarn pit gnammas were entirely absent from the desert rockholes. There are few staging points in the desert for bugs and beetles whereas on the Yilgarn Craton there are many farm dams and some larger artificial water bodies that can serve a refuges during dry periods. Additionally, as with birds, the small opening size of such rockholes as pipe gnammas may militate against access by active invertebrate dispersers.

Acknowledgements: We thank Ian Elliot for the collection from the Bartlett Bluff rockhole, and for his skillful navigation along the Hann Track. Ian Elliot, Paul Kennedy and Diane Sullivan assisted with the field work during the August–September expedition and are thanked for so doing. We gratefully acknowledge Greg Dempster for his assistance in preparing Figures 1 and 2. Joan Powling is thanked for the identification of *Euglypha*. Patrick De Deckker kindly provided a copy of one geological reference.

References

Bayly I A E 1997 Invertebrates of temporary waters in gnammas on granite outcrops in Western Australia. Journal of the Royal Society of Western Australia 80: 167–172.

Beard J S 2002 Palaeogeography and drainage evolution in the Gibson and Great Victoria Deserts, Western Australia. Journal of the Royal Society of Western Australia 85: 17–29.

BMR Palaeogeographic Group 1990 Australia: Evolution of a Continent. Bureau of Mineral Resources, Canberra.

Bohonak A J & Jenkins D G 2003 Ecological and evolutionary significance of dispersal by freshwater invertebrates. Ecology Letters 6: 783–796.

Donaldson M & Elliot I (eds) 1998 Do Not Yield to Despair: Frank Hann's Exploration Diaries in the Arid Interior of Australia. Hesperian Press, Carlisle.

Green A J, Jenkins K M, Bell D, Morris P J & Kingsford R T 2008. The potential role of waterbirds in dispersing invertebrates and plants in arid Australia. Freshwater Biology 53: 380–392.

Hulsmans A, Moreau K, De Meester L, Riddoch B J & Brendonck L 2007 Direct and indirect measures of dispersal in the fairy shrimp *Brachipodopsis wolfi* indicate a small-scale isolation-by-distance pattern. Limnology & Oceanography 52: 676– 684.

Iasky R P 1990 Officer Basin. *In*: Geology and Mineral Resources of Western Australia. Geological Survey of Western Australia Memoir 3: 362–380.

Jenkins D G 1995 Dispersal-limited zooplankton distribution and community composition in new ponds. Hydrobiologia 313/314: 15–20.

Jenkins D G & Underwood M O 1998. Zooplankton may not disperse readily in wind, rain or waterfowl. Hydrobiologia 387/388: 15–21.

Jocqué M, Timms B V & Brendonck L 2007 A contribution on the biodiversity and conservation of the freshwater fauna of rocky outcrops in the central Wheatbelt of Western Australia. Journal of the Royal Society of Western Australia 90: 137–142.

Jocqué M, Vanschoenwinkel B & Brendonck L 2010 Freshwater rock pools: a review of habitat characteristics, faunal diversity and conservation value. Freshwater Biology 55: 1587–1602.

Myers J S & Hocking R M 1998 Geological Map of Western Australia, 1: 2,500,000. Geological Survey of Western Australia, Perth.

Pinder A M, Halse S A, Shiel R J & McRae J M 2000 Granite outcrop pools in south-western Australia: foci of diversification and refugia for aquatic invertebrates. Journal of the Royal Society of Western Australia 83: 149–161.

Roberts D 2004 Prolonged survival of eggs of the rock pool mosquito, *Aedes vittatus*, in the extreme heat of the Arabian Peninsula. Journal of Arid Environments 57: 63–70.

Service M W 1997 Mosquito (Diptera: Culicidae) dispersal: the long and short of it. Journal of Medical Entomology 34: 579–588.

Silcock J 2009 Identification of Permanent Refuge Waterbodies in the Cooper Creek & Georgina-Diamantina River Catchments for Queensland and South Australia. South Australian Arid Lands Natural Resources Management Board, Port Augusta.

Therriault T W & Kolasa J 2001 Desiccation frequency reduces species diversity and predictability of community structure in coastal rock pools. Israel Journal of Zoology 47: 477–489.

Timms B V 2006 The large branchiopods of gnammas (rockholes) in Australia. Journal of the Royal Society of Western Australia 89: 163–173.

Twidale C R & Campbell E M 2005 Australian Landforms. Rosenberg Publishing, Kenthurst.

Twidale C R & Corbin E M 1963 Gnammas. Revue de Géomorphologie Dynamique 14: 1–20.

Wellborn G A, Skelly D K & Werner E E 1996 Mechanisms creating community structure across a freshwater habitat gradient. Annual Review of Ecology & Systematics 27: 337–363.

Journal of the Royal Society of Western Australia, 94: 557–581, 2011

The petroglyphs of the Kybra Aboriginal Site, South-Western Western Australia

R G Gunn [1], J Dortch [2], C Ogleby [3] & A Thorn [4]

[1] 329 Mt Dryden Road, Lake Lonsdale, Vic. 3381
✉ gunnb@activ8.net.au

[2] Dortch & Cuthbert Pty. Ltd., PO Box 1583, Fremantle, WA 6160
✉ joe.dortch@westnet.com.au

[3] Department of Geomatics, University of Melbourne, Vic. 3010
✉ clogleby@unimelb.edu.au

[4] Artcare Pty. Ltd., 2 McCabe Place, North Melbourne, Vic. 3051
✉ artcare@iprimus.com.au

Manuscript received April 2011; accepted August 2011

Abstract

The Kybra Aboriginal Site is the largest and most important petroglyph site in south-western Australia. It holds immense cultural significance, symbolising the Dreaming of Kybra, a giant bird, and being an important camping and ceremonial place in Bibbulmun Nyoongar land. The site is now located in a cleared farm paddock in the Scott River Region of the south coast of Western Australia. It comprises some 267 petroglyphs on horizontal limestone sheets, dominated by the tracks of birds and animals, and previous researchers have considered it to be an isolated example of the Australia-wide Panaramitee petroglyph tradition. This paper documents the petroglyphs and their context to assist with a later re-assessment of their status in relation to the Panaramitee.

Keywords: Petroglyphs, South-west Western Australia, Panaramitee Tradition

Introduction

On the basis that the Kybra petroglyph site contained a predominance of macropod and bird track motifs, Clarke (1983) and later Franklin (1992, 2004, 2007a) proposed that it belonged to the "Panaramitee Style" or Tradition (see Maynard 1976:182–199; Flood 1997, but note Rosenfeld 1991; Bednarik 1995). Maynard considered the style (erroneously) to be Australia's earliest art tradition although, at the time of her study, the Kybra site had not been reported and so was not considered. In a later re-evaluation of the Panaramitee style, Franklin (1992) included the Kybra site due to its similarity with other peripheral sites mentioned by Maynard. She counted 75 motifs at the site and was cautious of Clarke's 1983 claim of more than 100 motifs (1992: 50). Franklin (2007a) further concluded that not only was the Kybra site a peripheral site of the Panaramitee style, its existence could be explained by what she termed the "discontinuous Dreaming network model", that linked petroglyph sites across the continent by a web of Pleistocene and early-mid Holocene Dreaming Tracks (contra David 2002).

The Kybra Aboriginal site, DIA Site ID 4882 (also known as the Scott River or Milyeannup site), is on the southern coast of Western Australia, some 260 kilometres south of Perth (Fig. 1). Despite the local distribution of apparently suitable rock exposures, no other petroglyphs are known in this region (DIA files). Three other open petroglyph sites have been reported on granite hills to south-east of Perth (DIA files from Davidson 1952; Wolfe-Okongwu 1978), but recent investigation found them all to be natural markings (Webb and Gunn 2004). Petroglyphs have also been reported from three deep cave sites to the north (Hallam 1972, 1975; Bednarik 1987/88, 1998) but, while of definite Aboriginal origin, they consist of sets of parallel finger-flutings and possess no similarities to the open Kybra petroglyphs. The most common Aboriginal heritage sites within 50km of the Kybra site are surface exposures of stone artefacts, representing past camping or manufacturing sites (DIA Site Files). Hence, the Kybra petroglyph site complex is highly unusual and therefore particularly significant among the Nyoongar sites and places of the south-west.

Research background

The first account of the site was published in "People" magazine in 1962 where it was stated that the markings were fossilised bird footprints. This claim was investigated by Alex Baynes, of the Western Australian Museum, and John Clarke, from the Department of Conservation and Environment, Perth. They determined the petroglyphs were cultural rather than natural markings and gave a description of the site and its environment (Clarke 1983). Clarke suggested the petroglyphs were early Holocene in age (Clarke 1983) but, following the publication of dated "Panaramitee" style petroglyphs from South Australia that reportedly ranged from c.1000 BP to 33,000 BP in age (Nobbs & Dorn 1985), he revised his estimate to a likely late Holocene age (Clarke 1989). [These proposed dates however were subsequently withdrawn by Dorn (1997)]. Clarke estimated there to be over 100 "engravings" on some 25

Figure 1. Location of the Kybra site in SW Western Australia and the extent of the Noongar NT claim

"blocks" (1983: 64). He found the motifs consisted mostly of bird tracks, but also macropod tracks (both forepaws and hind feet), star-shapes, single wandering-lines, and boomerang-shaped outlines (ibid.). Clarke noted the singular and isolated occurrence, and hence high archaeological significance, of the site, and concluded his report with a number of urgent conservation and management recommendations, but none of these were implemented by the management authorities.

Natalie Franklin included the Kybra site (then known as the Scott River site) in an examination of the variation within the so-called Panaramitee Tradition across Australia (Franklin 1992: 224–225 & 241, Plates 13A & B). She located and classified 75 motifs and provided the first tracing of the petroglyphs, which clearly show the linear character of the motifs. Like Clarke, she found the suite here to be dominated by "bird" and "macropod" track motifs (47% and 21% respectively). Compared with other Panaramitee sites across Australia, the Kybra suite was small and homogeneous (see also Franklin 2004, 2007a&b), and most similar to two sites in central and northern Queensland, on the opposite side of the continent over 3000 km away. It was found to have little in common with her closest Panaramitee site at Edah, in the Murchison region, some 700 km to the north. This supported the notion that the site is indeed an isolated cultural feature.

Later, Stephen Corsini (1997) undertook a management study of the site and produced scaled-

Figure 2. View of the Kybra site prior to excavations (2005)

drawings of the visible motifs and slabs following removal of some overgrowing vegetation. He proposed that the petroglyphs were produced as a form of "sympathetic hunting magic": an interpretative paradigm that has long been considered inappropriate to Australian rock art (cf. Morwood 2002; Whitley 2005).

The site setting

The petroglyphs occur within a low-lying paddock on the flood plain of the Scott River in the south-west of Western Australia. The location is separated from the coast, three kilometres to the south, by a ridge of vegetated sand dunes reaching to 50 m above sea level (Dortch *et al.* 2006). Clarke concluded from the vegetation that the area was originally a swampy plain prior to its draining for agriculture (1983: 63). The paddock is presently used for cattle pasture (Fig. 2).

Unconsolidated sand dunes now border the southern and western sides of the site. The sand plain for many kilometres to the north and east of the site, which has an average elevation of 16m above sea level, is seasonally flooded and poorly drained. Consequently, the sediments surrounding the petroglyph slabs are seasonally waterlogged.

The rock can be described as a limestone of open porous structure, possibly formed in a waterlogged swamp environment, or possibly through stromatolite formation (Dortch *et al.* 2006). The movement of the water-table over time is probably critical to both its formation and deterioration. Continuing geological investigations are aimed at clarifying both the rocks' formation and age.

The regional climate is Mediterranean with mostly dry, hot summers and wet, cool winters. The average annual rainfall is around 1000 mm; with the predominant wind directions from the SE and NW (Bureau of Meteorology 2004). Mean daily maximum temperatures range from 25° C in February to 16° C in July, highest recorded temperatures are 43° C in February and 4° C in September. Frosts have not been recorded. There are at least 6 rain-days per month in summer, and up to 25 in winter; giving the potential for plant growth throughout much of the year. As the site is fully exposed, the pavements housing the petroglyphs are subject to the full impact of rainfall, flooding, and insolation.

The swampy coastal plain features many resources used by Nyoongar people and the estuaries and wetlands could have supported significant gatherings in spring and summer. The woodland and forest associations around Kybra would have supported many resources used by Nyoongar people as they were the habitats of c.60 species of favoured mammals, birds, and reptiles, and the source of c.80 edible and collected species of plants (Dortch 2004). These areas would have been easily accessible, since rivers in south-western Australia also defined routes for pathways. Crossing points on large rivers are likely to have been important "nodes" (pathway intersections) in the Nyoongar landscape. The chains of swamps and wetlands across the Scott Coastal Plain would have provided waterfowl, turtles, frogs, freshwater crayfish, and edible rhizomes (reed roots), used by Nyoongar people particularly in spring and summer, as well as providing permanent water. River mouths and inlets in south-western Australia also enabled fish-trapping on a large scale, which supported large gatherings. Details of the pathways and nodes in the Scott Coastal Plain are presently unknown but the proximity of the river and the Hardy Inlet, 10–20 km to the west, means that the site was probably located in an area important to Nyoongar people in the past. Further inland, food resources were scattered, and any given location could not support long occupations or large numbers of people.

The most common tracks represented in the petroglyphs are consistent with those of fauna commonly seen around the site today: *i.e.* three-toed bird track – emu (*Dromaius novaehollandiae*) and narrow opposed-tick tracks – western-grey kangaroo (*Macropus fuliginosus*). Both are well-known Nyoongar food animals, but which also have social and mythical associations.

Aboriginal associations

The site is within the area of the south-western cultural group known as the Bibbulmun (or Bibelmen or Pibelmen), a territorial group within the Nyoongar language group covering all of south-western Australia (Berndt 1979, Tindale 1974). The Bibbulmun people occupied the south-western Australian coast and hinterland from the Blackwood River in the west to Broke Inlet (or possibly further) in the east. Their neighbours were the Wardandi to the west and north-west, the Kaneang to the north, and the Minang (Meneang) to the east. Descent from one or more of these territorial groups is commonly claimed among many Nyoongar people today.

The site's traditional custodians recount that the area was the home of *Kybra*, a giant white bird who at some time in the distant past flew westward out to sea where its wings could still be seen on the horizon from time to time. The white sails of European sailing ships likely to have been frequently visible on the western horizon in the 17th, 18th and 19th centuries, could have been identified as the wings of *Kybra*, signalling his return. Today, the petroglyphs are associated with the *Kybra* Dreaming. *Kybra*, or *Kibbera*, means "ship" in Nyoongar vocabularies from the Busselton and Albany areas (Bindon and Chadwick 1992). The historic vocabularies suggest that *Kybra* came to mean "ship", at least for some Nyoongars, by the 1830s–1840s.

The location of the site near natural fords on the Blackwood River suggests that the area is also a likely place for inter-group meetings and gatherings, particularly between Bibbulmun people and their neighbours to the west, the Wardandi, for marriage-partner exchange (Goode and Irvine 2006).

Before European colonisation, Nyoongar people foraged in different parts of their respective territories according to seasonal abundances of resources and social needs, and under a system of inherited land tenure and cultural and ritual obligations. The archaeological record shows that Aboriginal occupation of the immediate region has been continuous for at least the last 45,000 years (Dortch 2004, Turney *et al.* 2001). Nearby sites also show that Aboriginal people used the Scott Coastal Plain and adjacent areas throughout many changes in

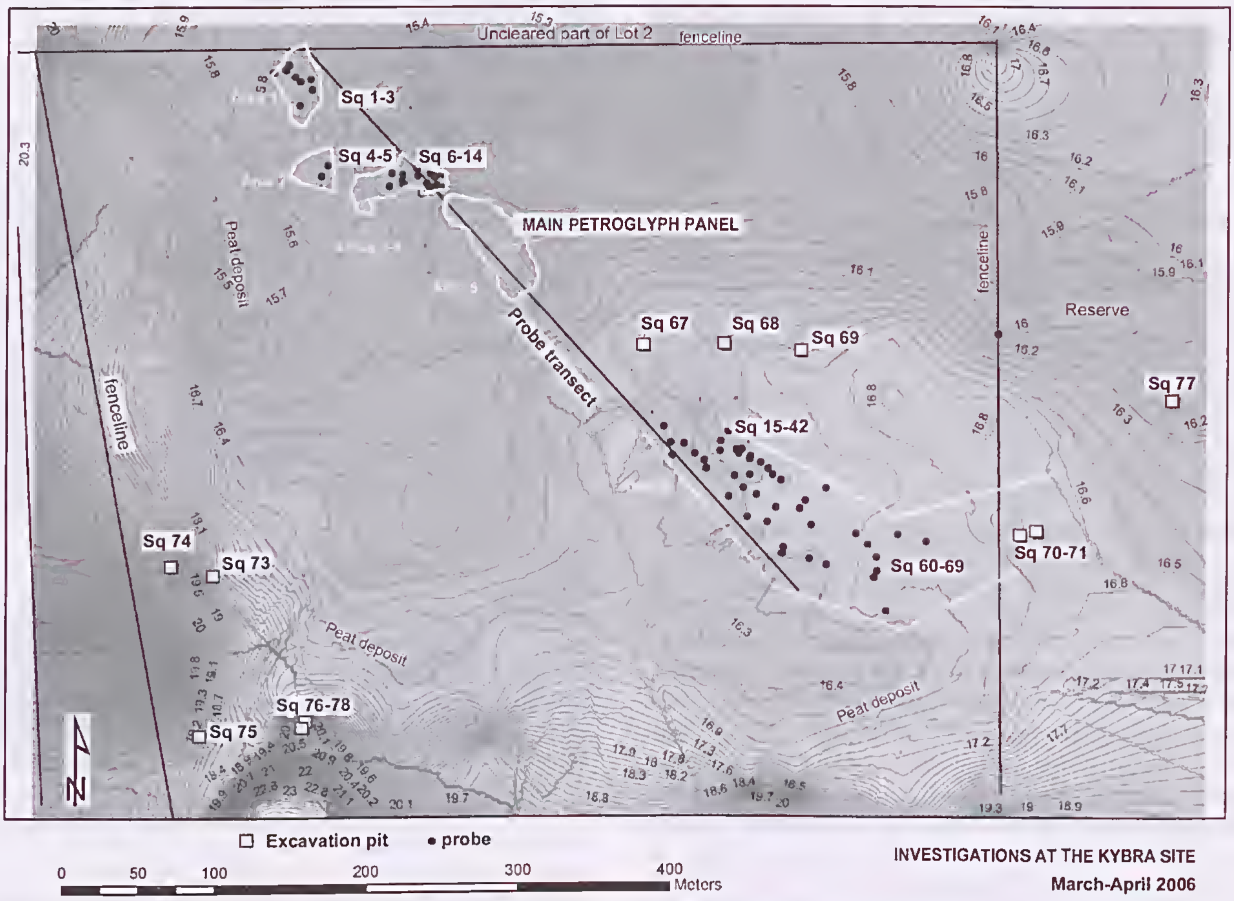


Figure 3. Plan of the Kybra site showing location of petroglyph areas, probe transects and excavation pits

Figure 4. The exposed area showing the fractured nature of the bedrock. Most of the smooth rocks bear petroglyphs

environment, include sea-level rise caused by post-glacial global warming. The absence of evidence for major population disruptions despite these environmental changes supports the notion that these people had a highly flexible and resilient economy that sustained a similar way of life for many millennia.

Despite experiencing massacres and introduced diseases, Nyoongar people retained connections to the lower south-west in colonial times (Hammond 1833, Bates 1985). In the Scott River and the Margaret River regions, "King" Bungaitch and "Queen" Ginny were widely recognised as elders belonging to those areas. Nyoongar families in the south-west maintain their association with ancestral Bibbulmun or Wardandi territory though hunting, fishing, and gathering, and passing down oral histories.

The present survey

Before the present survey, the full extent of the petroglyphs had not been determined (Clarke 1983; Franklin 1994, 2004). Consequently, pedestrian surveys were undertaken of other rock outcrops to the north-east and east but only a single other petroglyph was located (400m to the east; Dortch *et al.* 2006). Within the 40ha site paddock, sub-surface probe survey, using 40cm survey pins inserted on a 20m grid, showed limestone at depths of 5–40cm extending in a NW–SE orientation across the paddock, through the main area of engravings, and into eastern outcrops (Fig. 3). The survey team inspected six sheets of limestone identified in the paddock by removing grass and sand with hand tools at 67 locations, each c.1m^2, but found petroglyphs only on sheet 5 (modern plough damage was also seen on this and two other sheets). At sheet 5, another c.1,000 m^2 of sediment and grass was then removed to expose the bulk of limestone and several previously unrecorded petroglyphs (Fig. 4). The paddock, archaeological features (including engravings and test-excavations) and areas of exposed rock were then mapped using a Leica 1200 total station (see below).

To improve understanding of the use of the area, the team conducted eight test-excavations on the paddock and nearby, within 100–300m of sheet 5 (Fig. 3). Only two test-excavations, on the dunes south and west of the paddock, contained artefacts. These slightly elevated locations, beside former springs, gave views of the petroglyph area and surrounding country. The small, highly reduced quartz artefacts suggest prolonged residential or base camping with few logistical camps or forays during each episode of occupation. Charcoal associated with artefacts in the upper 50cm of square 74 is dated 1500–1800 BP and 2500–2800 BP (calibrated to calendar years). These results suggest that Nyoongar people have camped for prolonged periods at Kybra throughout a period of more than 2,800 years.

Figure 5. Detail of the rock pavement showing abrupt edges (Panels E09 foreground)

Figure 6. Excavation pit at the edge of the rock pavement showing upper crust which becomes more clay-rich and friable with depth. (Pit width 25 cm).

The rock

Clarke (1983) considered the rock in which the petroglyphs are pecked to be a limestone-like calcitic crust, formed as a result of algal mats in a shallow lake depositing the calcite during dry conditions. This forms a broken pavement, some 75x25m in area and around 0.2m thick. The edges of the petroglyph panels are partially buried by regrowth and soil, but the greater majority of rock, and hence the bulk of motifs, are now exposed. Following excavation, the edges of the panels were found to be both abrupt and crenulated (Fig. 5).

The rock substrate varies from a substantially calcitic crust to a more clay rich and friable structure at the underside (Fig. 6). The sheet is interrupted with many channels, fractures and holes that in some cases penetrate through the upper few centimetres of the crust (Fig. 7).

An analysed sample of the rock contained sub-rounded to rounded quartz grains within an overall porous matrix with several continuous tunnels and voids. Some voids appear to be collapsed shell-like structures although only a single fragment of shell was found within the calcite. Under low magnification it appears to be fine-grained and evenly wrapped around the quartz

Figure 7. Vermicular surface of the rock showing vegetation attracting cracks (Panel E02)

Figure 8. Rain filled petroglyphs after 4 days of light drizzle totalling 3.2mm (Panel E13)

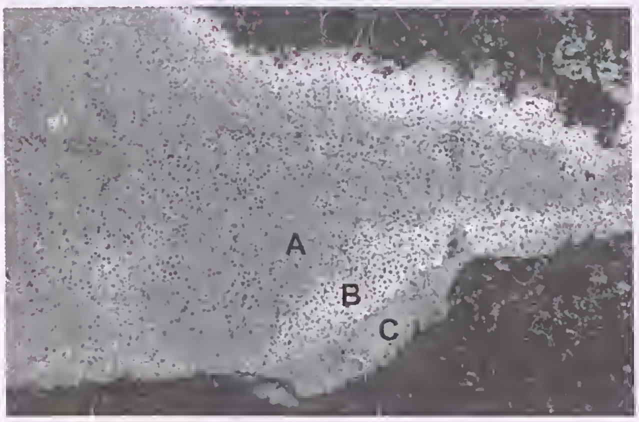


Figure 9. The three surface zones of dissolution. A: grey inner surface – moderately stable, B: white band of redeposited material – more stable, C: brown out surface previously covered by soil – moderately stable but subject to root destruction (Panel F01).

in a precipitation-type relationship with no evidence of deposited particles that may indicate a calcarenite-type formation. A polarising Light Microscopy analysis showed no evidence of coccoliths or other animal structure, and the calcite particles were all fine-grained with no evidence of larger nodules. The calcite character is consistent with a calcrete-type formation and not any other. There is evidence of charcoal particles within the rock, indicating a surface or near-surface formation environment.

The exposed nature of the site ensures that the rock surface is flushed after each heavy rain. It was observed that even small showers can fill the petroglyphs (Fig. 8) and it is expected that heavier rain would wash all soluble ions off the slabs. Soluble ions in this case include calcium sulphate that will have formed through combination of calcium from the rock with atmospheric sulphur. The water within the petroglyphs however, will be retained much longer, creating a protracted acidic pool that, in theory, should cause more rapid erosion within the petroglyphs, ensuring that they continue to deepen more rapidly than the surrounding rock. However at the site there is variable evidence of dissolution within the petroglyphs themselves and on the whole there is no topographic difference between the inner walls of a petroglyph and the sheet surface into which it has been pecked. It is apparent that plants have caused more damage to the surface of the petroglyphs than to areas of the rock that have been exposed for longer periods. The vermiculated surface shows the extent of root penetration and grain loss. Grass roots not only exert mechanical forces but also provide a highly acidic local environment that will rapidly dissolve the calcite. It is not possible to say whether the roots have created these channels or have simply taken advantage of a pre-existing natural nutrient supply.

Three weathering zones are apparent on the exposed slabs (Fig. 9):

A- Inner grey surface surrounding the engraving is moderately stable but has detaching sand grains and a high lichen colonization.

B- White band of redeposited material lies between the exposed rock and recently soil covered rock. This zone has no exposed sand grains and appears more stable. Stability here depends very much on whether the precipitate is gypsum or calcite.

C- Brown surface indicating recently soil covered rock. This area is as stable as the grey exposed surface but has much more root growth and deeper channelling.

Also, it is difficult to explain why the majority of petroglyphs have an identical topography to surrounding rock, while a few, such as motifs 183 and 192, have a very smooth interior surface. As this is unlikely to be the result of a selective natural process, they may have been reworked by abrading.

As the 75% calcite content, by dissolution in hydrochloric acid, can allow this to be called limestone (>50%), it is considered that the nature of the relationship of the deposited calcite coating and binding quartz particles is worthy of a more specific description. It is noted that that it is not calcarenite. The term "calcitic crust" is more appropriate as it implies the calcite has acted as a binder to the quartz. This may not be absolutely correct as a classification as some definitions of calcrete indicate the non-calcitic component should be alkaline. Here we have chosen to define the nature of the precipitated calcite from solution, including the presence of charcoal, rather than compaction of calcite grains and coccoliths *etc.* In essence it is a conglomerate of surficial sand and gravel cemented into a hard mass by calcium carbonate, which has been precipitated from solution and redeposited through the agency of infiltrating waters, or deposited by the escape of carbon dioxide from vadose water. The specimen studied conforms to each of the key principles here.

The sample can therefore be described as a limestone of open porous structure, possibly resulting from an intermittently flooding environment, or as is suggested here, through stromatolite formation. The presence of charcoal indicates the formation has developed while in its current position in relation to surrounding soil levels for at least part of its formation life. The pavement would have thus formed many millennia ago, creating a puzzle as to how the fragile rock has survived to the present day. Clarke's (1983) hypothesis that it may have been

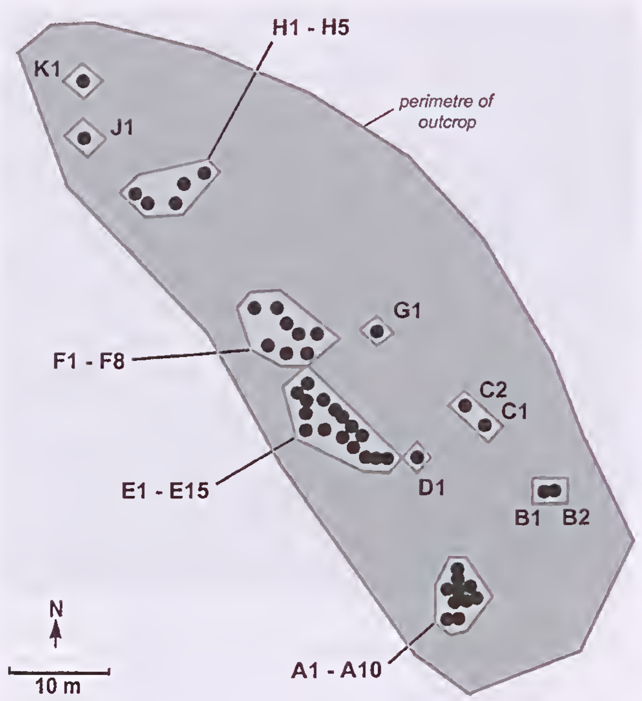


Figure 10. GPS plot of the petroglyph panels A–K

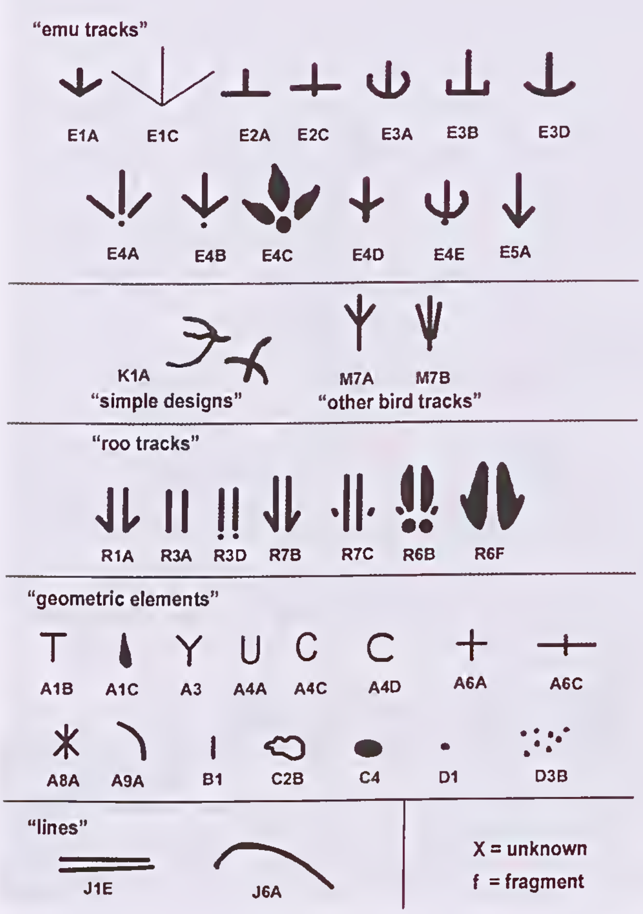


Figure 11. Motif types at Kybra

due to it being covered by sand dunes after the period of petroglyph production and then later re-exposed by wind erosion is feasible.

Impacts from both bulldozer tracks and scalloped plough discs occur across the southern and eastern sections of the site, but the overwhelming concern for its preservation is the extreme fragility of the rock and its vulnerability to erosion, whether in the form of rain, pooling water, or soil moisture.

The Rock Art recording

The petroglyphs were located in ten clusters on the main outcrop (A–K; Fig. 10) and one 400m to the east (L). A total of 267 motifs were recorded. Of these 240 could be classified by type, with the other 27 being relegated to a class of fragments (Table 1; Fig. 11). The motifs were dominated by tracks (66%: emu tracks 45%) and geometric elements (31%) and are mostly between 50mm and 200mm in length. A few instances of superimposition testify to the site's re-use over a prolonged, but unknown, period. All of the motifs are heavily weathered but the form of most remains well defined.

The petroglyphs occur on forty-seven panels, ranging from 0.14 m^2 to 15 m^2 in area (median 0.64 m^2), with maximum widths ranging from 0.5 m to 5 m (median 1.2 m). The number of motifs per panel ranged from 1 to 55, with a median of 2. Thirty-eight panels had less than 10 motifs, and 13 had only a single motif. The number of motifs on each panel was unrelated to the size of the panel (Fig. 12).

The present project undertook four methods of recording of each of the petroglyph panels. First freehand sketching was undertaken to locate and designate all the motifs. This was followed by detailed photographic record on a digital camera (Fujipics 6500) and then by laser scanning. Subsequent to the fieldwork,

Table 1

Motif class percentages

MOTIF CLASS	No.	%	*No of types*
emu tks	116	48	*13*
roo tks	36	15	*7*
geometric elements	30	13	*10*
bars	26	11	*1*
dots	12	5	*2*
other bird tracks	8	3	*2*
lines	4	2	*2*
simple design	3	1	*1*
unknown	3	1	*3*
ovals	2	1	*2*
TOTAL	**240**	**100**	***41***
fragments	27		

MOTIF GROUP	No	%
Tracks	160	67
Geometric elements	74	31
Other	6	3
TOTAL	**240**	**101**
fragments	27	
(n)	267	

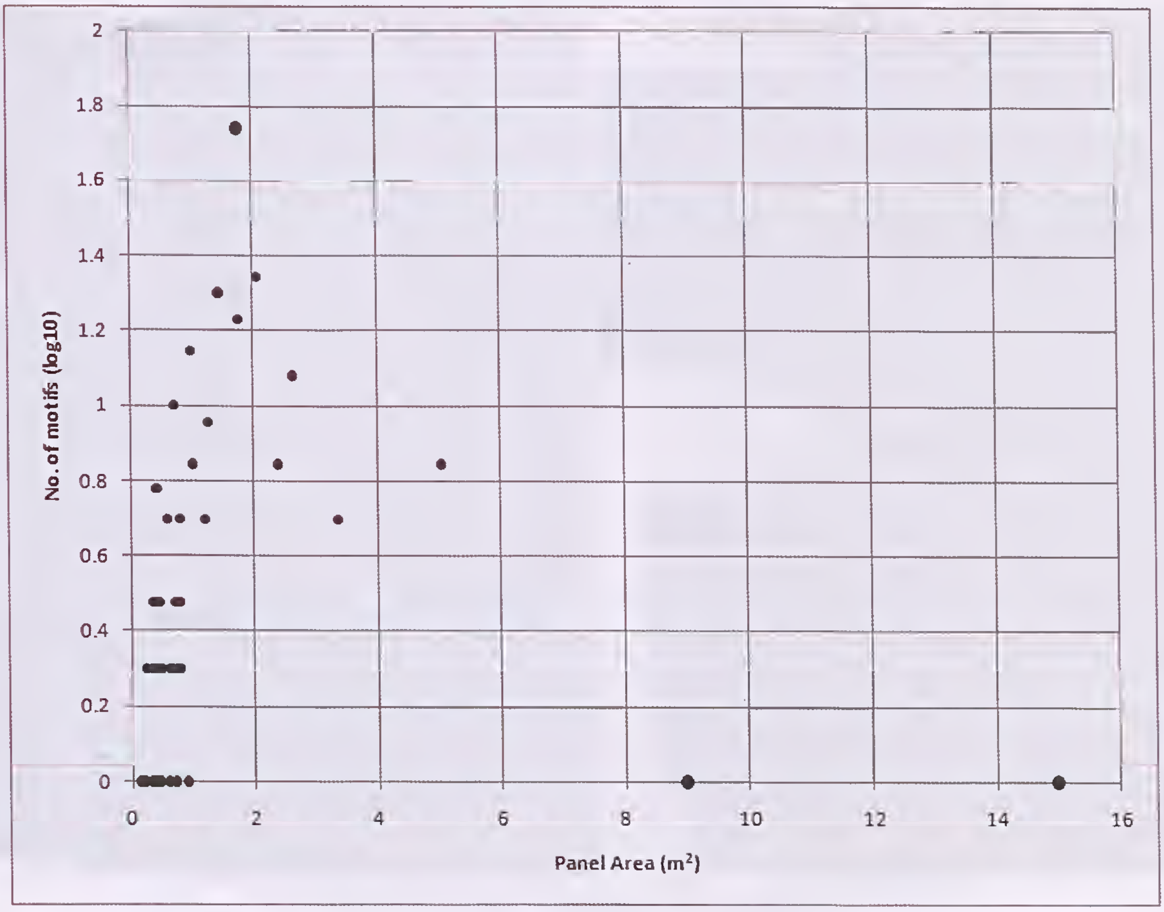


Figure 12. Plot of motif number per panel by panel size

detailed tracings were produced of select panels from enlargements from the photographic record.

The Laser-Scanning record

Three-dimensional laser-scanning systems are a recent development in the process of acquiring 3D records of complex surfaces. There is a wide variety of instrument types, ranging from long-range machines designed for topographic and mining applications, through to those designed for sub-millimetre accuracies on small artefacts and the human body.

The short-range instruments generally use visible laser with a similar data acquisition rate, but giving a much higher accuracy and precision. The Konica Minolta Vivid 910 used here uses a laser triangulation process, where a camera on the instrument records the laser profile as it is passed over the surface being measured. As this unit used relatively low-power visible laser, the scanner had to be insulated from sunlight. Since this project the scanner is now housed in a light-reducing tent on a lightweight trolley, but at the time it was necessary to undertake the scanning at night. The scanner was mounted vertically above the rock platform on a tripod, which also supported a laptop computer and a light. The scans covered a surface area of around $0.25m^2$, and scan areas were overlapped to provide a comprehensive panel cover. The overlapping scans were later stitched together in the scan-processing software.

An arbitrary coordinate system was established on site, which was later connected to the Map Grid of Australia (MGA) using a Leica GPS unit. The GPS observations were processed using the Auspos service, which allows high accuracy positioning with one GPS unit. Position control for each panel of art/scans was established using a combination of 3D targets and natural features, surveyed using a Leica "total station". This was to enable the recording of the correct position and orientation of each set of stitched scans on the site.

The data acquisition process resulted in topographic measurements of the site, along with over 100 scans of the motifs. The scanner obtains detailed shape data, along with a low-resolution image of the surface (Fig. 13). This is effectively a micro-DEM (digital elevation model) and can be studied using a variety of spatial analysis operations often found in Geographic Information Systems (GIS) if the need arises. Using software it is possible to produce a colour map of the surface with the colours indicating depth variation. As the data is a set of three-dimensional measurements, it is also possible to rotate the surface so that it can be viewed or studied from almost any vantage point, and with illumination from any angle (Fig. 14).

The complete digital data for the surface models are now available for future analysis such as minute measurement of erosion. The data is also suitable for the production of facsimile panels for public display.

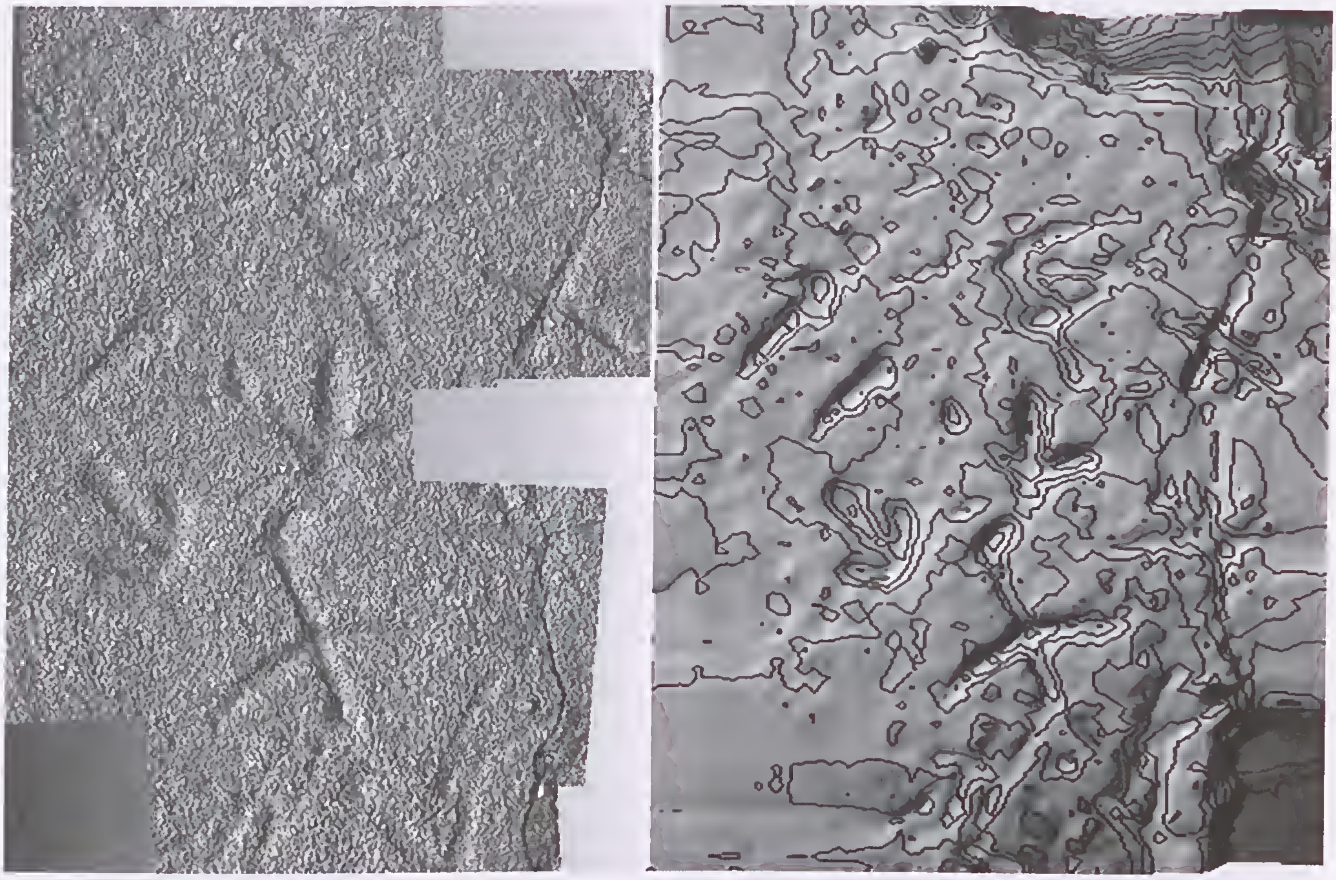


Figure 13. Example of a micro-digital elevation model of the petroglyphs and contour map of the same area

Freehand sketching and tracing

Freehand sketches were undertaken of all panels showing the approximate shape of the panel, its orientation, and the shape and placement of the petroglyphs. This allowed careful observation of each motif from which its motif type, form, and any superimpositioning were described, and its longest axis measured. The tracings were produced from enlarged digital photographs, using a variety of enhancement applications to achieve maximum interpretation. These applications were restricted to increasing and decreasing contrast rather than utilising the applications more commonly used for coloured motifs (cf. David *et al.* 2001; Gunn *et al.* 2010).

Motif numbers and distribution

A total of 47 panels with 267 motifs were located at the site (Figs 3 and 10; Appendix 1). Panels were distinguished by the physical perimeter of each slab and, while some motif distributions and arrangements reflect existing slab forms, others have been clearly disrupted by the present erosional patterns. Consequently, panel degradation has occurred since the production of the petroglyphs and the nominated panels cannot be seen to fully reflect the available rock surfaces at the time the petroglyphs were made. The number of motifs per panel ranged from 1 to 55, with a median of 2 (Figs 15–20). Six panels had more than 10 motifs, but 63% had less than five motifs, and 28% had only a single motif. The artwork is not evenly distributed across the site but is concentrated in the central area (group E; Fig. 10) and with a greater density to the south than to the north. This pattern, however, is not reflected in the areas of available surface as the larger panels occur at the northern end (groups H–K), suggesting either that the concentration is an artefact of use or that less of the northern panels were exposed and available at the time of motif production.

Panel E2, near the centre of the main group, has 55 motifs (Figs 15 and 16), which is more than twice that of any other panel. The arrangement and distribution of the motifs on this panel closely parallels the current perimeter of the rock slab and is therefore likely to reflect the shape of the panel when the motifs were produced. The panel also appears to have seven instances of superimposition and three stages of weathering suggesting that the motifs were produced over a considerable, but unknown, period of time. Consequently, this dense and central panel is taken to be the focus for the petroglyphs.

Panel L, 500m east of the main cluster, is a singular outlier with five motifs on a small slab (0.5x0.4m). Although fractured, the presence of adjacent undecorated panels suggests that the panel was the work of a single person or event, rather than part of a substantial sub-site (cf. Clegg 1987).

Motif types

Thirty-nine distinct types (or subjects) were recorded from the motif suite, with an additional class for

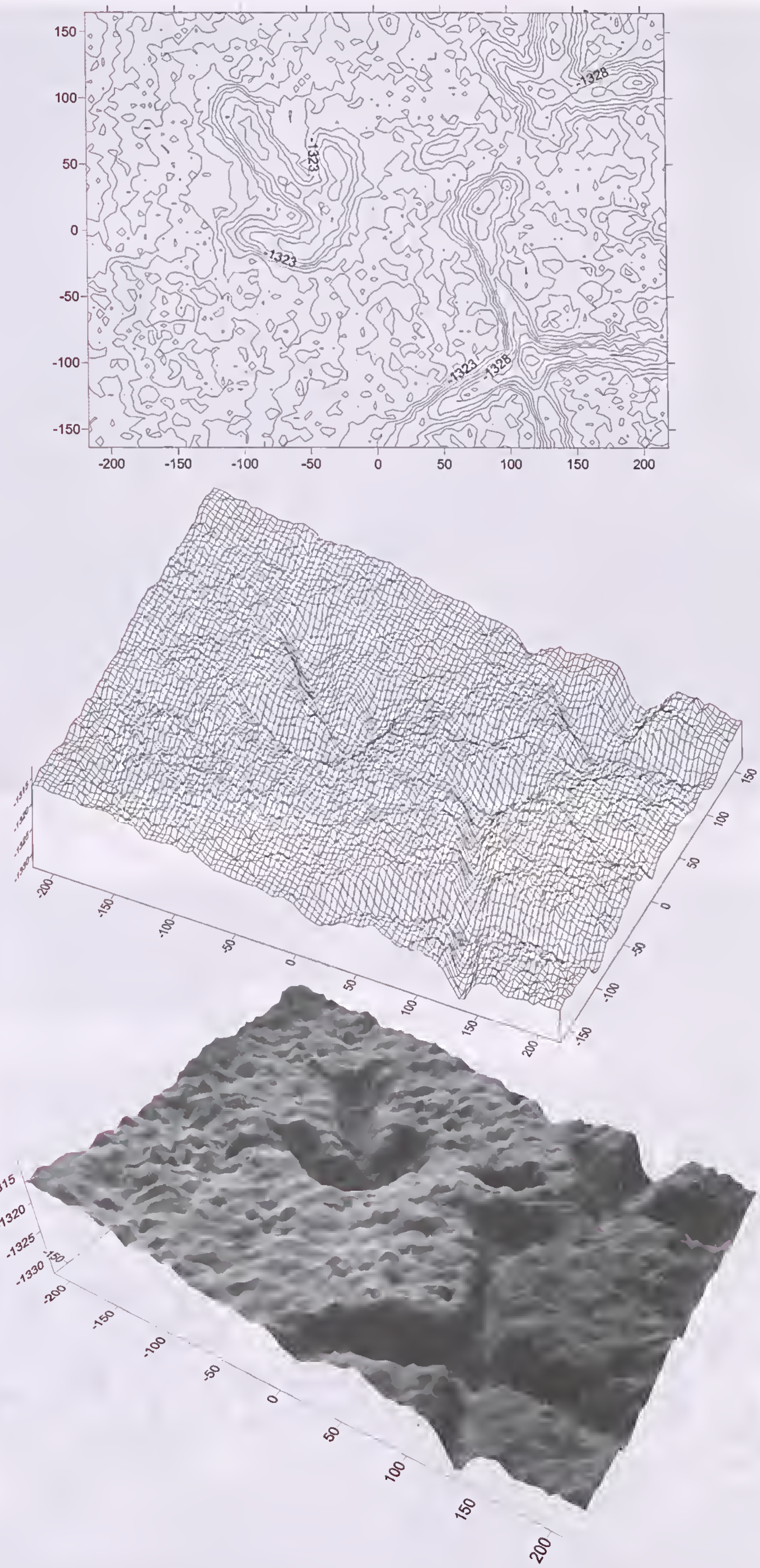


Figure 14. Scanner plot showing rotational model and artificial enhanced lighting

Figure 15. Vertical photograph of Panel E02

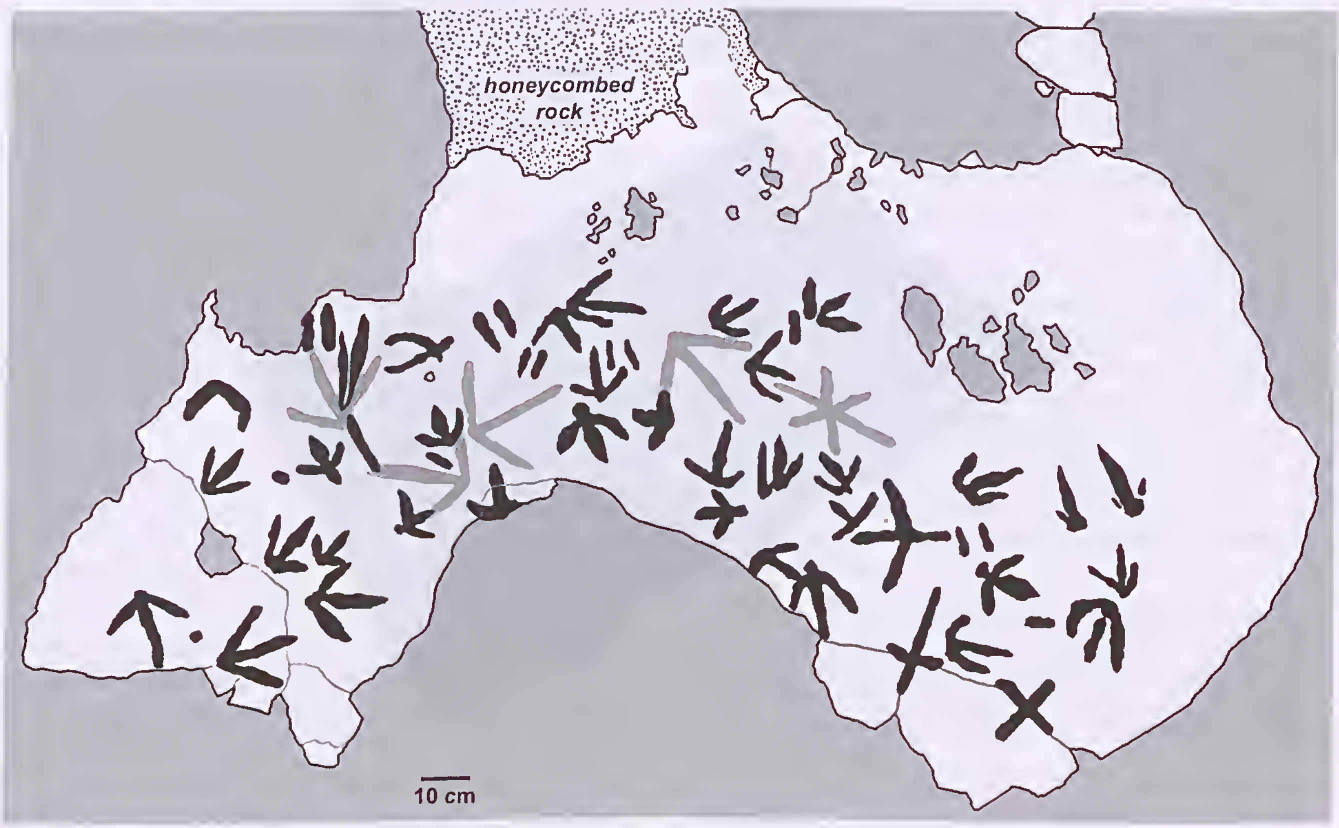


Figure 16. Photo-tracing of Panel E02: the densest and most highly decorated of the panels

Figure 17. Panel E10: the second most highly decorated panel

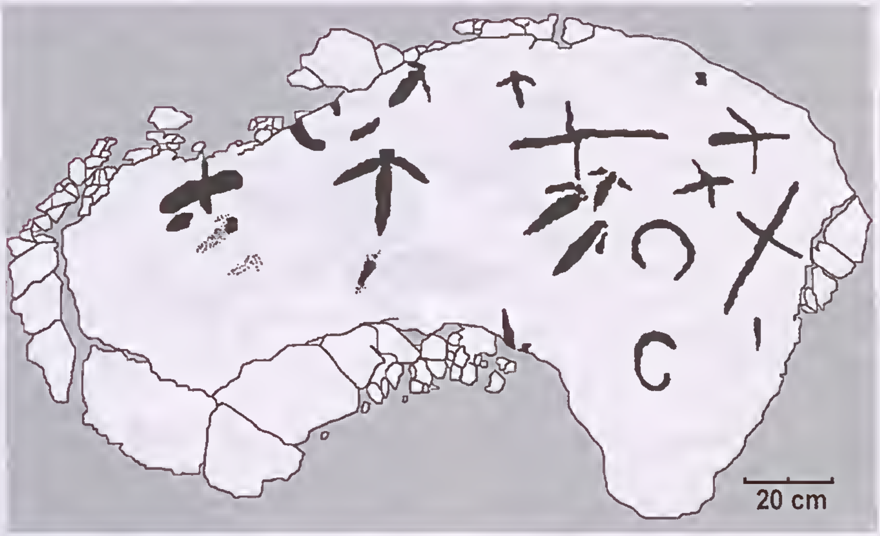


Figure 18. Panel E11: the third most decorated panel

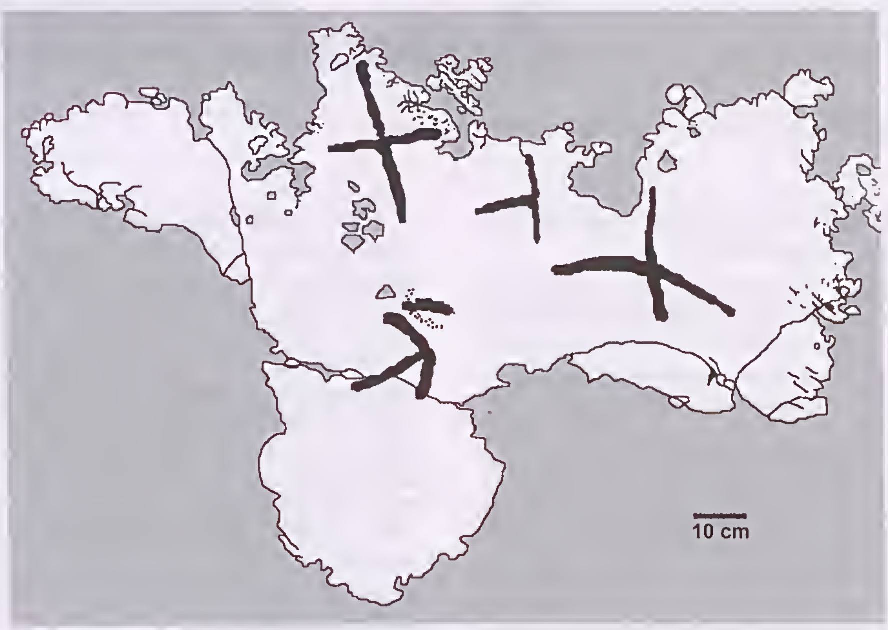


Figure 19. Panel E06 with distinctive 'long-cross' motifs

Figure 20. Panel F1 with the largest (0.68m) and smallest (0.15m) of the 'long-cross' motifs

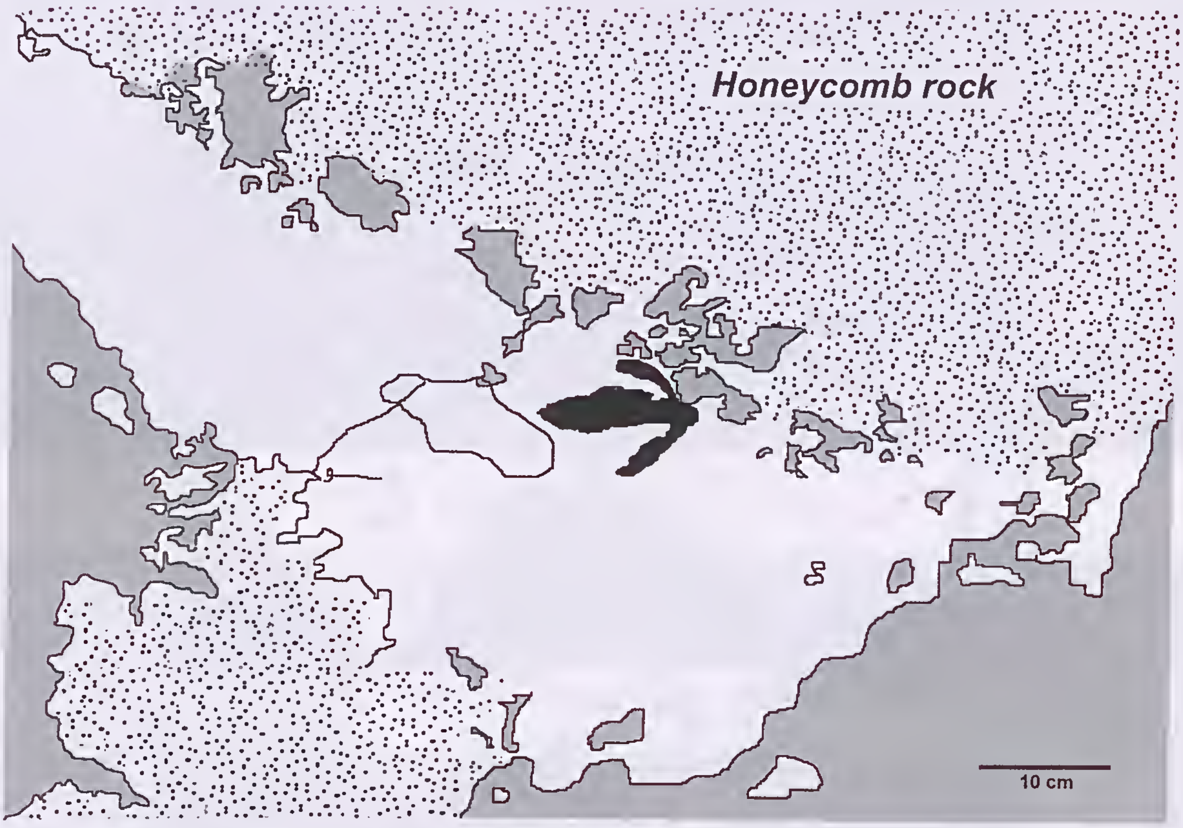


Figure 21. Panel C1: one of the least decorated but more representative panels

"unknown" (unrecognised) types and another for fragments (Table 1; Fig. 11; Appendix 2).

Interpreting a number of the motifs was problematic due to their poor condition and the similarity in colour between the motif and the surface of surrounding rock. Even raking light failed to clearly delineate the shape of some of the motifs. Consequently, a few motifs were recorded differently when drawn at the site and when later traced from photographs. In this instance, it was the field recording that was used in the analysis, although traced photographs more accurately reveal the shape of most motifs and their proximal relationship to other motifs. Also, it was found that by using artificial lighting at night, both the shape and size of a motif could be significantly distorted depending on the placement of the light source.

Their deteriorated state also made determining the original form of the motif very difficult. For example some "emu track" motifs have a distinct heel whereas others do not. It is possible that some of those without a heel originally had one but, with weathering, the distinction between the heel and toes has been eroded away leaving a linear shape. In some examples there is variation with depth, presumably due to erosion. In these cases the rim of the petroglyph displays a linear form, but the depth shows the differentiation of the pads. Whether the apparent pads are part of an erosional process of the lower portions of the motif, or the linear shape is due to the erosion of the upper parts is unclear. For this study however, the existing shape is what has been recorded, on the presumption that, for general analysis, such fine-grained sub-division may be meaningless.

Table 2

Emu track motif sub-type percentages

Motif sub-type	No	%
e1a	46	*40*
e5a	16	*14*
e3d	11	*9*
e4b*	10	*9*
e1c	7	*6*
e3a	7	*6*
e2c	3	*3*
e3b	3	*3*
e4a*	3	*3*
e4c*	3	*3*
e4d	3	*3*
e2a	2	*2*
e4e	2	*2*
TOTAL	**116**	*103*

* heels distinct

Numerically (122 or 51%) and visually, the artwork is dominated by bird tracks (*e.g.* Fig. 17). A total of 15 types of bird tracks occur, thirteen of which are generic "emu tracks" (tracks of emu, bustard, waders, *etc*), and two are four-toed tracks (such as heron). The most common variety is the standard "arrow" emu track (type e1a 40%; Table 2), with the second most common the "long-toed arrow" form (e5a: 14%). Those varieties with distinct heels (types e4a, e4b, and e4c) together form only a minor group (15%).

The next largest group, macropod tracks, had seven varieties with the most common being a simple pair of short parallel bars (type r3a: 56%; Table 3; Fig. 12). As with the emu tracks, those tracks with distinct heels are in the minority (11%).

The other types that stand out are "long-crosses" (type e6c), "C" shapes (a4c), and "horseshoe" shapes (a4d). The former occur on three panels (E6, E11 and F1), each in close proximity and all with two examples (*e.g.* Figs 18–21). While all six are the same shape however, they vary greatly in size, from the largest motif recorded here, at 68cm, to small 15cm, with three around 35cm.

Table 3

Roo track motif sub-type percentages

Motif sub-type	No	%
r3a	20	*56*
r1a	7	*19*
r6b*	3	*8*
r6f	3	*8*
r3d*	1	*3*
r7b	1	*3*
r7c	1	*3*
TOTAL	36	*100*

* heels distinct

The six "C" shapes (Fig. 11) are widely distributed across the site and show no common motif associations. Along with the three horseshoe shapes, they are the only "circular-shaped" motifs at the site. All are between 8cm and 15cm wide and are neither large nor imposing, and none are central to any of their respective panels.

There is a positive correlation between the number of motifs per panel and the number of types represented (Fig. 22). This suggests that panels were not the focus of particular motif types but rather each was an accumulation of a general suite that operated across the site. Unlike Maynard's finding for Panaramitee sites (1976), where similar motifs tended to form discrete clusters, the reverse seems to occur here. This then suggests the aggregation of the long-crosses mentioned above is contrary to the general arrangement, making it all the more significant.

Techniques and patination

The degree of motif weathering across the site and the nature of the rock makes it difficult to determine the production technique used here, and in most cases it is no longer possible to be definite regarding technique.

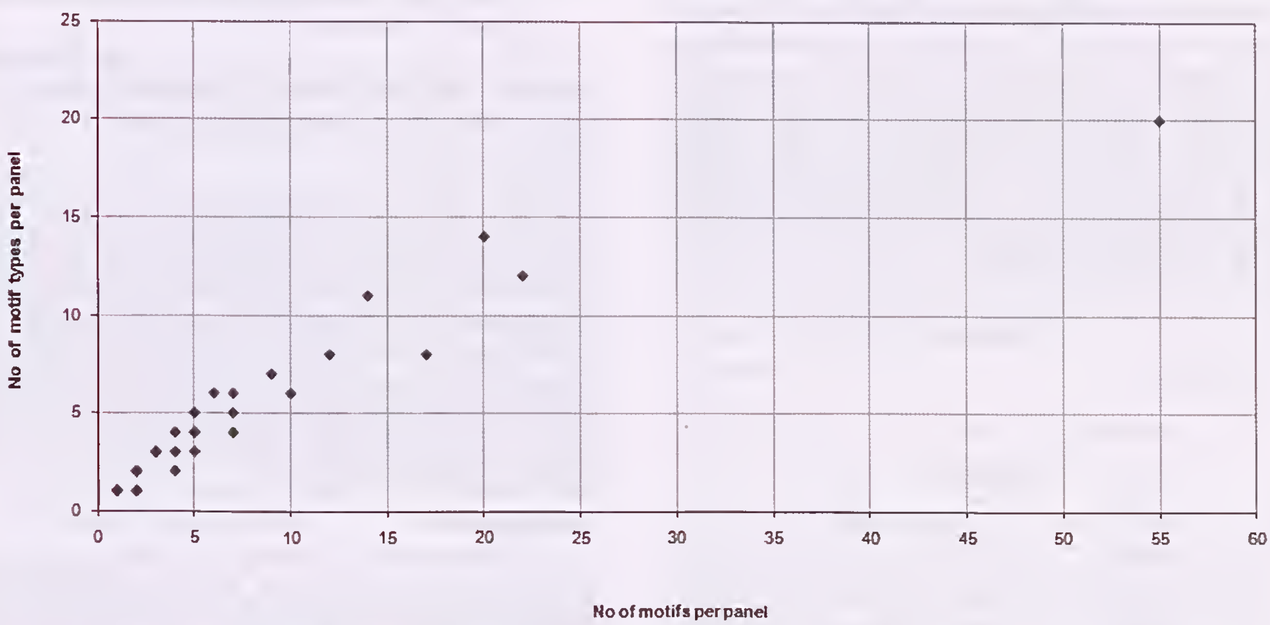


Figure 22. Motif types numbers by the number of motifs per panel

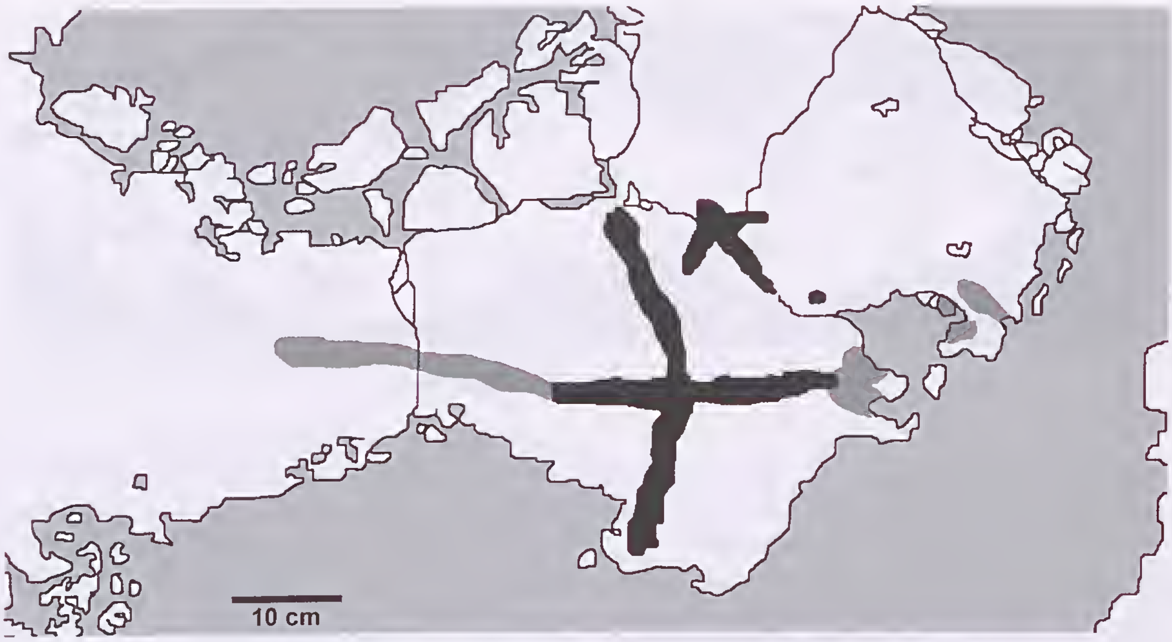


Figure 23. Panel A5 with superimposed or partially altered motif

The presence of a few motifs with distinct heel pads depicted suggests that the motifs were pecked. Although pounding could have been used, elsewhere in Australia there is no record of it being used for such deep motifs. At least five of the motifs were produced by abrasion, however, as in many petroglyph sites, the abrading appears to be a reworking of earlier pecked motifs.

All of the motifs have weathered back to the colour of the surrounding rock (Fig. 7), however none contain any patina. The lack of patina may be the result of either the rock type, inappropriate climate for patina formation, or subsequent degradation by weathering.

Forms

Motif form is the manner in which it is constructed: dotted, linear, solid, outline, outline plus infill, or any combination of these. The repertoire here was limited to six different form types (Table 4). These consisted of four basic types: linear (78%), solid (18%), outline, and dot (each <1%); and two combination forms: linear+dot and solid+linear (both <5%). The dominance of linear motifs is clear and appears to be a hallmark of the repertoire that contrasts with the pattern of the Panaramitee which tends to have a high proportion of outlined, circular motifs (circles, concentric circles *etc.*).

Table 4

Form frequencies

Form type	No	%
dot (d)	2	*<1*
linear (l)	186	*78*
l+d	3	*1*
outline	1	*<1*
solid (s)	43	*18*
s+l	4	*2*
Total	**239**	***100***
fragments	28	

The single outlined motif is a 29cm, irregular circle on panel A6, although one other motif in the same area (panel A4) may have had a similar outline form that has since deteriorated.

Sizes

The motifs ranged from 3cm to 68cm in length, with a mean of 13cm, a median of 12cm, and a standard deviation of 8cm (n = 213). Most were less than 20cm (92%), and only 3% (6) were greater than 30cm. These largest motifs consisted of:

- four long-crosses: 34cm, 38cm(x2), 68cm (motif type A6A),
- a simple design 38cm, and
- an unknown linear type 52cm (superimposed and utilised by a subsequent motif).

As the size of available panels was not a limiting factor, the homogeneity of the majority of motif sizes and types again points to a very singular repertoire.

Condition

Motif condition ranged from fair to very poor, with none in an excellent or good condition. The overall weathered condition suggests either a rock type unsuitable for the long-term preservation of petroglyphs or, alternatively, a considerable age for the motifs. In a few cases the weathering of the motifs has broken through the crust rock into the underlying sands with the result that only a negative outline of the original motif remains. It is highly likely that other motifs have been totally destroyed in this manner.

Superimposition

Several examples of overlapping motifs occur but, due to the poor preservation of the motifs involved, no sequence of superimposition can be determined. For example, all of the large "linear emu tracks" are superimposed by smaller "standard emu tracks" (Fig.

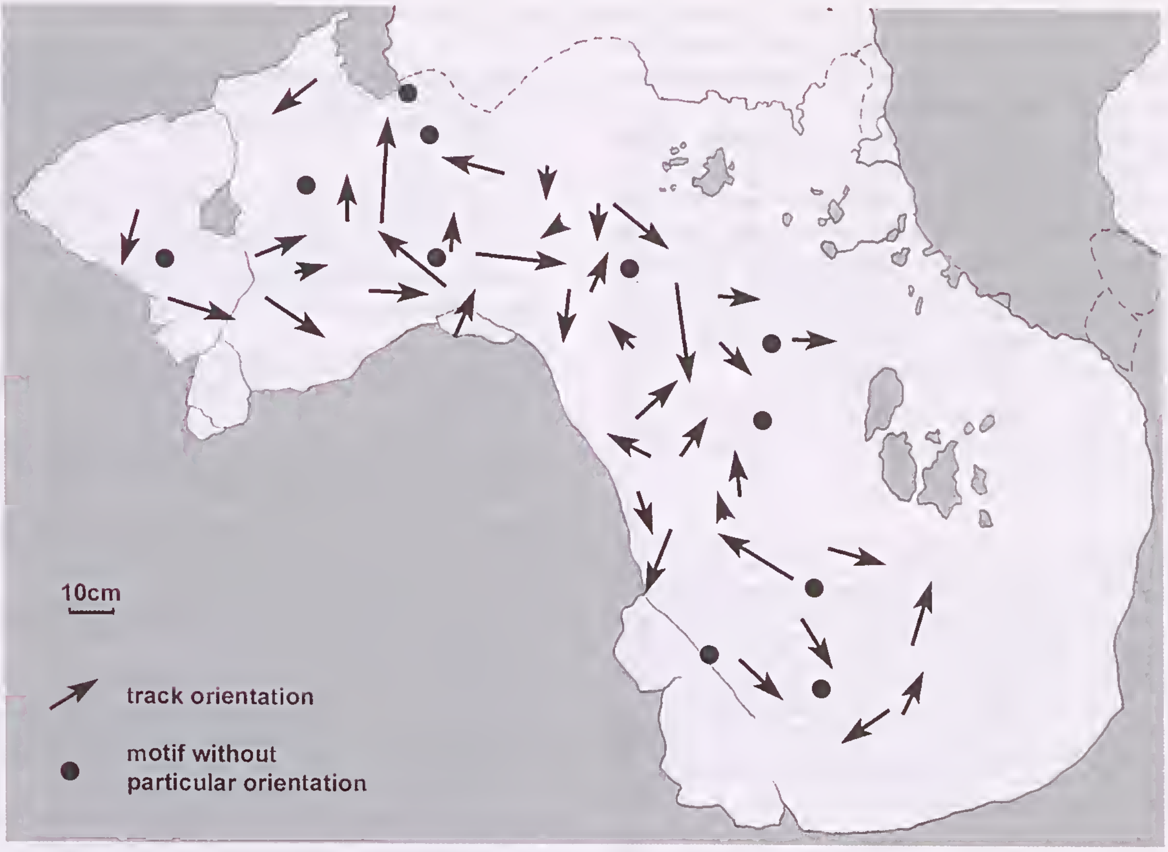


Figure 24. Motif orientation on Panel E02.

16), but in some instances the linear forms appear more recent while in others they appear less well preserved. The clearest example of superimposition occurs on panel A5 where a cross motif appears to overlie an earlier long-cross (Fig. 23). It is not clear, however, whether the more recent motif has simply "revitalised" a previous small section of the long-cross, or whether it represents a completely new motif (in which case the earlier motif may not have been a long-cross at all).

Compositions

No clear examples of composition were recorded. While some panels show aggregates of the same motif type, in many cases these exhibit different forms suggesting either that they were not contemporary or that they in fact represent different species (Figs 16–18 and 20). Even given the possibility of erosion producing some of the differences, the variable states of weathering would also indicate chronological differentiation. Examination of the orientation of the track motifs on the largest panel (Fig. 24) shows no consistent alignment or associations (such as track trails). It also suggests that the motifs were not produced as a series (such as by the one artist sitting in one spot or several artists working together). The lack of any such compositions, particularly involving trails of animal tracks, is another aspect where this site differs from a classic Panaramitee site.

Chronology

No chronology of the artwork can be provided as yet. On the basis of the rocks weathering potential, Clarke (1983, 1989) suggested that if the motifs were of Pleistocene age then they would have had to be preserved under a protective layer of sand (sand dune) or, if they had not been covered, they must be of late Holocene age.

On the basis of the superimposition and differential weathering states of the motifs across the site, it is likely that the suite of petroglyphs represents development over a considerable time rather than during a single episode or short period. However, at this stage, no limits can be put on the age of either the earliest or latest of the petroglyphs.

Inspection revealed a scatter of stone artefacts and charcoal on the surface and in excavations on the eastern slopes of the dune bordering the plain. Given the swampy nature of the plain, this is the most likely place for Aboriginal people to have camped when visiting the site and hence these scatters should be seen as part of the overall site complex. Consequently, as the charcoal was dated to the last 3000 years, it is possible that the petroglyphs were produced during this period of occupation, although the association remains speculative at present.

Conclusion

To the Nyoongar people, the area of the site was the home of *Kybra*, a giant white bird who at some time in the distant past flew westward out to sea where its wings could still be seen on the horizon from time to time. The association of the petroglyphs with this belief gives them a very high significance from a Nyoongar perspective.

From an archaeological perspective, as the Kybra Aboriginal place is the only petroglyph site reported from the south-western corner of Western Australia, it is again accorded a very high significance.

The motifs are dominated by "emu track" motif types (51%), with smaller numbers of "roo tracks" and "geometric elements". While these are elements of the Panaramitee Tradition, the total lack of any figurative motifs (lizards, stick figures, snakes, *etc*), trails of track motifs, and other elementary compositions, along with the almost total lack of circular motifs (circles, concentric circles, starred circles, *etc*), indicates that this they do not constitute a classic Panaramitee repertoire.

Further study of the calcite rock and direct dating of the rock itself will greatly assist in the interpretation of this very significant site.

Acknowledgements: The recording of the Kybra petroglyphs was undertaken with Bibbulmun-Wardandi custodian Wayne Webb in conjunction with a conservation and management assessment (Dortch *et al.* 2006) funded by the Restoring Connections Project: a jointly managed project between the South Coast NRM and South West catchments Council (SWCC). David Guilfoyle (Restoring Connections) supervised the project. Landowner David Dunnet provided access to the site. Further assistance was provided by Toni Watson and numerous volunteers. The excavation was done by a team from the Manjimup CDEP under the direction of JD. Leigh Douglas and two anonymous referees commented positively on the draft paper. The responsibility for the presentation and conclusions however, remains with the authors.

References

Bates D [White I ed.] 1985 The native tribes of Western Australia. National Library of Australia, Canberra.

Bednarik R G 1987/88 The cave art of Western Australia. The Artefact 12: 1–16.

Bednarik R G 1995 Taking the style out of the Panaramitee style. AURA Newsletter 12(1): 1–5.

Bednarik R G 1998 Direct dating results from Australian cave petroglyphs. Geoarchaeology 13(4): 411–418.

Berndt R M 1979 Aborigines of the South-West. *In*: Aborigines of the West (eds R Berndt & C H Berndt). University of Western Australia Press, Perth, 81–89.

Bindon P & Chadwick R 1992 A Nyoongar wordlist from the south-west of Western Australia. Western Australian Museum, Perth.

Clarke J 1983 An Aboriginal engraving site in the south-west of Western Australia. Records of the Western Australian Museum 11:63–67.

Clarke J 1989 Comment on Nobbs and Dorn 1988. Rock Art Research 6(1): 63–65.

Clegg J 1987 Style and tradition at Sturt's Meadows. World Archaeology 19: 236–255.

Corsini S 1997 Site management options: Milyeannup engravings, Scott River. Report to the Aboriginal Affairs Department, Southwest Regional Office, Albany.

David B 2002 Landscapes, rock-art and the Dreaming: an archaeology of preunderstanding. Leicester University Press, London.

David B, Brayer J, McNiven I J & Watchman A 2001 Why digital enhancement of rock paintings works: rescaling and saturating colours. Antiquity 75(2001): 781–792.

Davidson D S 1952 Notes on the pictographs and petroglyphs of Western Australia and a discussion of their affinities with appearances elsewhere on the continent. Proceedings of the American Philosophical Society 96: 76–117.

Dorn R I 1997 Uncertainties in 14C ages for petroglyphs from the Olary province, South Australia. Archaeology in Oceania 32: 214–215.

Dortch J 2004 Palaeo-environmental change and the persistence of human occupation in south-western Australian forests. British Archaeological Reports International Series S1288, Oxford.

Dortch J, Gunn R G, Ogleby C, Semeniuk V & Thorn A 2006 Milyeannup Aboriginal Dreaming and petroglyph site, south-western Australia. A report to Mr Wayne Webb, The Restoring Connections Program and Department of Indigenous Affairs (Heritage & Culture), Albany.

Flood J 1997 Rock art of the Dreamtime. Angus & Robertson, Sydney.

Franklin N R 1992 Explorations of variability in Australian prehistoric engravings. PhD thesis, La Trobe University, Melbourne.

Franklin N R 2004 Explorations of variability in Australian prehistoric engravings. British Archaeological Reports International Series 1318, Oxford.

Franklin N R 2007a Aboriginal engravings in the southwest of Western Australia: analysis of the Kybra site. Records of the Western Australian Museum 24: 65–79

Franklin N R 2007b Discontinuous Dreaming networks: analysis of variability in Australian pre-historic petroglyphs. Rock Art Research 24(1): 79–103.

Goode B & Irvine C 2003 A survey of Aboriginal social water requirements for the Southern Blackwood Plateau and the Scott Coastal Plain, Southwest, Western Australia. Unpublished report prepared for Department of Environment, Western Australia, January 2006.

Gunn R G, Ogleby C L, Lee D & Whear R L 2010 A method to visually rationalise superimposed pigment motifs. Rock Art Research 27(2): 131–136.

Hallam S J 1972 An archaeological study of the Perth area, Western Australia: a progress report on art and artefacts, dates and demography. Australian Institute of Aboriginal Studies Newsletter 3(5): 11–19.

Hallam S J 1975 Fire and Hearth. Australian Institute of Aboriginal Studies, Canberra.

Hammond J E 1980 (1933) Winjan's People. Facsimile edition, Hesperian Press, Victoria Park, Western Australia (original published by Imperial Printing Company, Perth).

Maynard L 1976 An archaeological approach to the study of Australian rock art. MA thesis, Department of Archaeology, University of Sydney.

Morwood M J 2002 Visions from the past: the archaeology of Australian Aboriginal art. Allen & Unwin, Crows Nest.

Nobbs M & Dorn R I 1988 Age determinations for rock varnish formations within petroglyphs" cation-ratio dating of 24 motifs from the Olary region, South Australia. Rock Art Research 5(2): 108–145.

Rosenfeld A 1991 Panaramitee: dead or alive? In: Rock art and Prehistory, (ed P Bahn and A Rosenfeld). Oxbow Monograph 10, Oxbow books, Oxford, 136–144.

Tindale N B 1974 Aboriginal tribes of Australia: their terrain, environmental controls, distribution, limits, and proper names. Australian National University Press, Canberra.

Turney C S M, Bird M I, Fifield L K, Roberts R G, Smith M, Dortch C E, Grun R, Lawson E, Ayliffe L K, Miller G H, Dortch J & Cresswell R G 2001 Early human occupation at Devil's Lair, southwestern Australia 50,000 years ago. Quaternary Research 55: 3–13.

Webb R E & Gunn R G 2004 Re-recording culturally significant sites in south-western Australia as a guide to Noongar usage of the region in the past. Rock Art Research 21(1): 93–97.

Whitley D S 2005 Introduction to rock art research. Left Coast Press, Walnut Creek.

Wolfe-Okongwu W 1978 Aboriginal art of south-west of Western Australia. BA (Hons) thesis, Dept of Anthropology, University of Western Australia.

Appendix 1

Kybra motif list
List of all motifs recorded by panel indicating their form type*, motif type and size (length)

Panel	Motif No	Form	Type	Size (cm)
A01	1	s	r3a	6
A01	2	s	r3a	6
A02	3	l	e3d	8
A02	4	s	r6f	
A03	5	s	e3d	8
A04	6	l	e1a	12
A04	7	s	e5a	7
A04	8	sl	e4a	13
A04	9	l	a4a	12
A04	10	l	b1	8
A04	11	l	f	23
A05	12a	l	m7a	30
A05	12b	l	x	52
A05	13	f	f	
A05	14	s	d1	3
A05	15	s	e1a	10
A06	16	s	r3a	6
A06	17	l	a9a	
A06	18	o	c2b	29
A07	19	l	e1a	10
A07	20	l	r7b	10
A08	21	s	r3a	7
A08	22	l	e3d	18
A08	23	l	j1e	15
A08	24	l	k1a	20
A08	25	l	k1a	17
A08	26	l	j1e	18
A08	27	f	f	
A09	28	l	k1a	38
A10	29	l	e1a	19
A10	30	s	e1a	8
A10	31	s	f	16
A10	32	s	r3a	
A10	33	l	m7b	20
A10	34	l	a4c	12
A10	35	f	f	
A10	36	l	e5a	16
A10	37	f	f	
A10	38	l	e1a	11
B01	39	l	b1	6
B02	40	s	r6f	11
B02	41	s	r3a	11
C01	42	l	e1a	10
C02	43	l	e3d	9
C02	44	l	e1a	13
C02	45	f	f	
C02	46	f	r7c	
D01	47	l	e4e	14
D01	48	l	e5a	12
D01	49	l	r1a	4
E01	50	l	r1a	13
E01	51	l	e5a	13
E02	52	l	m7d	17
E02	53	d	d1	3
E02	54	l	e1a	20
E02	55	l	e1a	17
E02	56	l	e1a	7
E02	57	l	e1a	15
E02	58	s	d1	4
E02	59	l	m7a	14
E02	60	l	a9a	16
E02	61	l	m7b	16
E02	62	s	r3a	9
E02	63	l	f	
E02	64	l	f	
E02	65	l	e1a	12
E02	66	l	m7d	26
E02	67	l	b1	7
E02	68	l	e1a	11
E02	69	l	m7d	21
E02	70	l	r3a	10
E02	71	l	e1a	14
E02	72	l	a4a	10
E02	73	l	r3a	
E02	74	l	r3a	
E02	75	l	e1a	14
E02	76	s	e1a	13
E02	77	l	e3d	
E02	78	l	m7d	21
E02	79	l	e4b	10
E02	80	l	e1a	11
E02	81	l	b1	8
E02	82	l	e3d	11
E02	83	l	e5a	15
E02	84	l	m7a	13
E02	85	l	e3a	13
E02	86	l	a8a	24
E02	87	l	e3b	
E02	88	l	e2a	9
E02	89	l	e2a	11
E02	90	l	e1a	13
E02	91	l	m7a	21
E02	92	s	e3b	14
E02	93	l	r1a	15
E02	94	s	r3a	5
E02	95	s	b1	4
E02	96	l	e1a	7
E02	97	l	e1a	11
E02	98	s	e4b	14
E02	99	l	a3	19
E02	100	l	e3a	9
E02	101	l	b1	6
E02	102	l	e1a	13
E02	103	l	a6a	18
E02	104	f	f	
E03	105	l	m7b	14
E04	106	s	e4b	
E05	107	l	e1a	
E06	108	l	a6c	38
E06	109	l	a1b	18
E06	110	l	a6c	38
E06	111	l	f	
E06	112	l	e3d	13
E07	113	l	b1	4
E07	114	s	b1	7
E08	115	l	e4b	14
E08	116	l	a4c	13
E09	117	l	e1a	
E09	118	l	b1	10
E09	119	f	f	
E09	120	l	e1a	12
E09	121	l	r1a	
E09	122	l	e3a	
E09	123	s	d1	
E09	124	l	m7d	29
E09	125	f	f	
E10	126	l	b1	
E10	127	l	r3a	7
E10	128	l	e1a	11
E10	129	l	m7d	13
E10	130	l	e1a	12
E10	131	f	f	

Panel	Motif No	Form	Type	Size (cm)
E10	132	l	f	
E10	133	l	e2c	
E10	134	l	b1	4
E10	135	l	a4d	8
E10	136	f	f	
E10	137	l	r6b	12
E10	138	s	b1	7
E10	139	sl	r6b	12
E10	140	l	b1	10
E10	141	l	a6a	24
E10	142	l	b1	8
E10	143	l	r3a	
E10	144	l	d3b	
E10	145	d	r1a	
E10	146	l	b1	6
E10	147	l	e3b	15
E11	148	sl	x	18
E11	149	s	a1c	
E11	150	f	f	
E11	151	l	j6a	13
E11	152	l	f	
E11	153	l	b1	
E11	154	l	e5a	15
E11	155	l	e4b	8
E11	156	sl	e4c	18
E11	157	l	a6c	34
E11	158	l	e5a	7
E11	159	l	r1a	16
E11	160	s	d1	4
E11	161	l	m7a	18
E11	162	l	e4b	10
E11	163	l	a6c	27
E11	164	l	a4d	14
E11	165	l	b1	7
E11	166	l	e5a	
E11	167	l	a4c	12
E12	168	l	e4b	13
E12	169	l	j1e	13
E12	170	s	a4a	7
E13	171	l	e1a	9
E13	172	l	e1a	13
E13	173	l	e3a	13
E13	174	l	e3a	15
E14	175	l	a6a	16
F01	176	l	e4a	12
F01	177	l	r3a	13
F01	178	l	a6c	15
F01	179	s	e4d	
F01	180	l	e2c	15
F01	181	s	d1	3
F01	182	s	b1	5
F01	183	s	e4e	15
F01	184	l	r6b	14
F01	185	s	e3d	18
F01	186	l	b1	9
F01	187	l	e4a	17
F01	188	l	e1a	14
F01	189	l	a6c	68
F02	190	l	r3a	10
F02	191	l	e4b	11
F02	192	l	e4b	18
F02	193	l	f	
F02	194	l	x	13
F02	195	l	f	
F02	196	l	r3a	8
F03	197	l	a9a	6
F03	198	s	d1	3
F03	199	f	f	
F03	200	s	d1	3
F03	201	l	b1	7

Panel	Motif No	Form	Type	Size (cm)
F03	202	s	c4	8
F03	203	l	e1a	5
F03	204	s	d1	3
F03	205	l	b1	4
F03	206	l	e5a	13
F03	207	l	e5a	13
F03	208	l	e4b	8
F04	209	l	e1a	11
G01	210	s	r3a	11
G01	211	l	e1a	12
H01	212	l	e5a	16
H01	213	f	f	
H01	214	l	e3d	8
H01	215	l	e1a	9
H01	216	ld	e4c	17
H02	217	l	e1a	10
H03	218	l	e4d	7
H03	219	l	e5a	13
H03	220	l	e5a	12
H03	221	l	e3a	11
H03	222	l	e3a	11
H04	223	l	b1	8
H04	224	l	e1a	12
H04	225	f	f	
H04	226	l	b1	6
H04	227	f	f	
H04	228	ld	r3d	10
H04	229	l	a1b	17
H04	230	l	e1a	7
H04	231	f	f	
H04	232	l	r3a	6
H04	233	l	e1a	7
H04	234	l	e1a	10
H04	235	l	e1a	9
H04	236	s	r3a	
H04	237	s	b1	
H04	238	ld	e4c	13
H04	239	l	e5a	16
H05	240	l	a4c	8
H05	241	l	a4c	8
H05	242	l	a4d	10
H05	243	s	r6f	10
H05	244	l	e2c	14
H05	245	l	e1a	13
H05	246	l	e4d	9
J01	247	l	e1a	10
K01	248	l	a4c	14
K01	249	l	b1	9
E15	250	l	e1a	
F05	251	l	r3a	6
F05	252	l	e5a	16
F06	253	l	b1	7
F06	254	l	a9a	10
F06	255	s	e1a	10
F07	256	s	d1	5
L01	257	l	e3d	15
L01	258	l	r1a	6
L01	259	l	e3d	9
L01	260	l	e5a	13
L01	261	f	f	
F08	262	l	f	
F08	263	s	d1	
F08	264	l	e1a	
E02	266	l	e1a	12
E02	267	l	e1c	

* **Form types:**

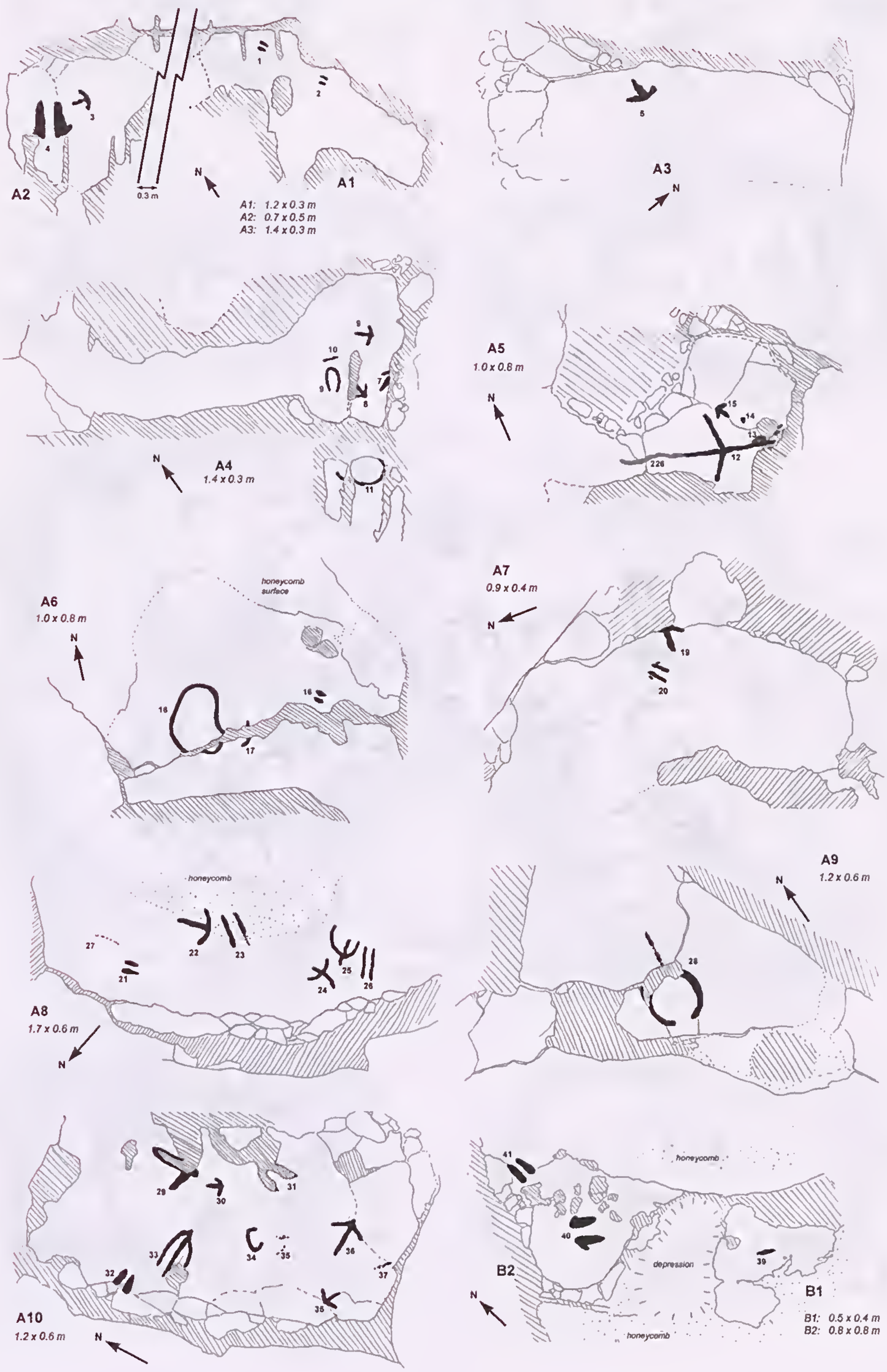
l = linear; ld = linear + dot; s = solid; sl = solid + linear; f = fragment.

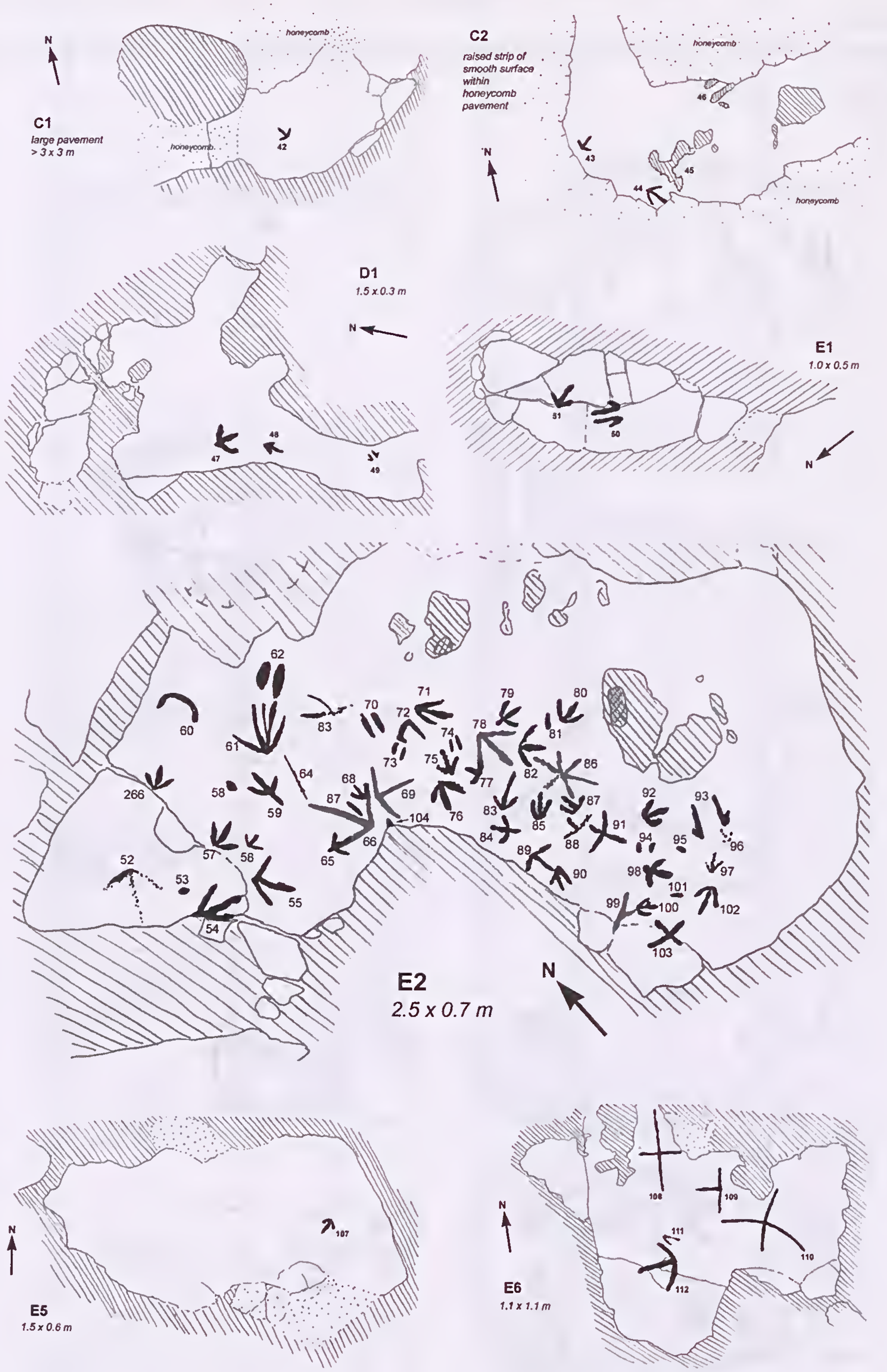
Appendix 2

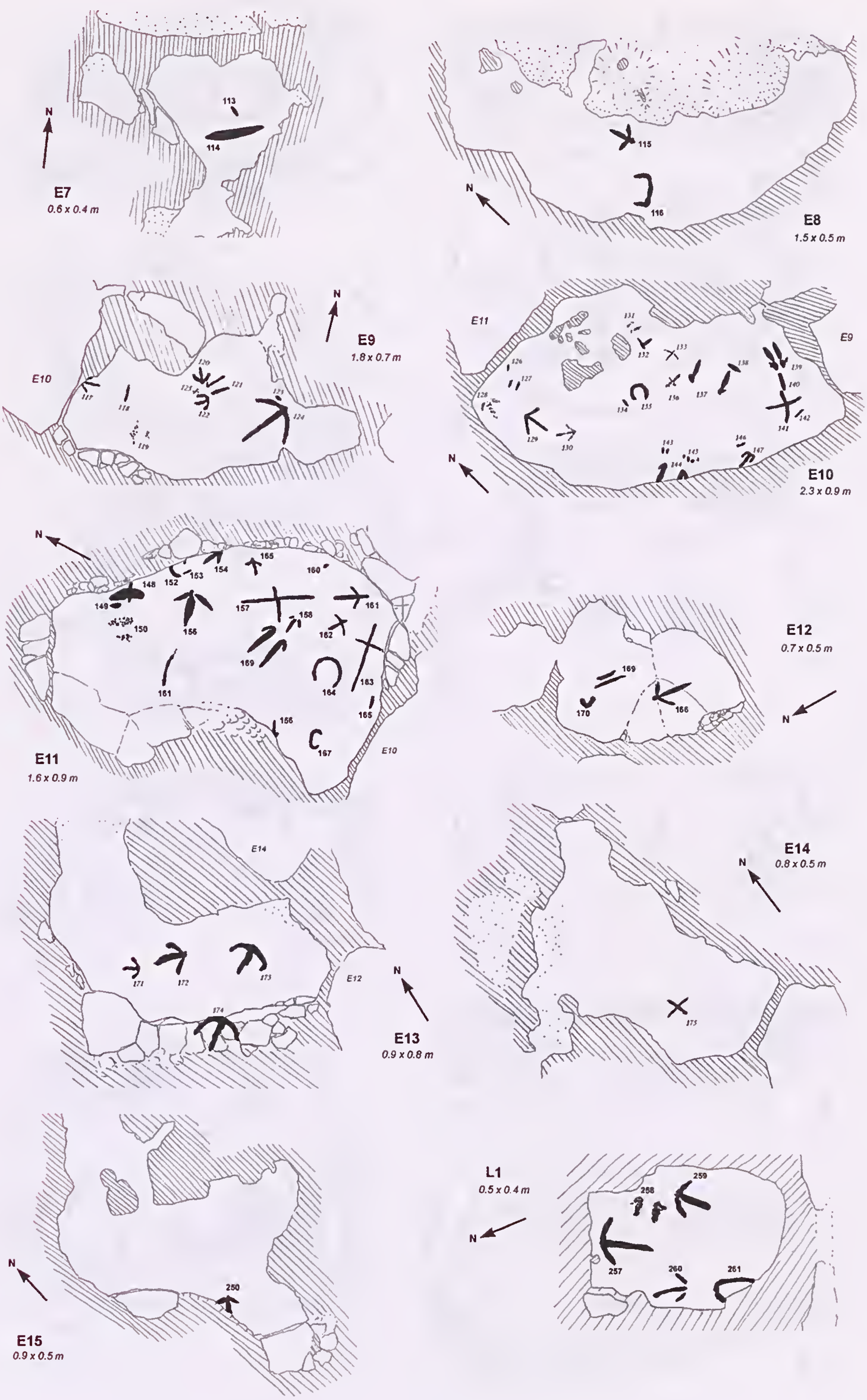
The art panels

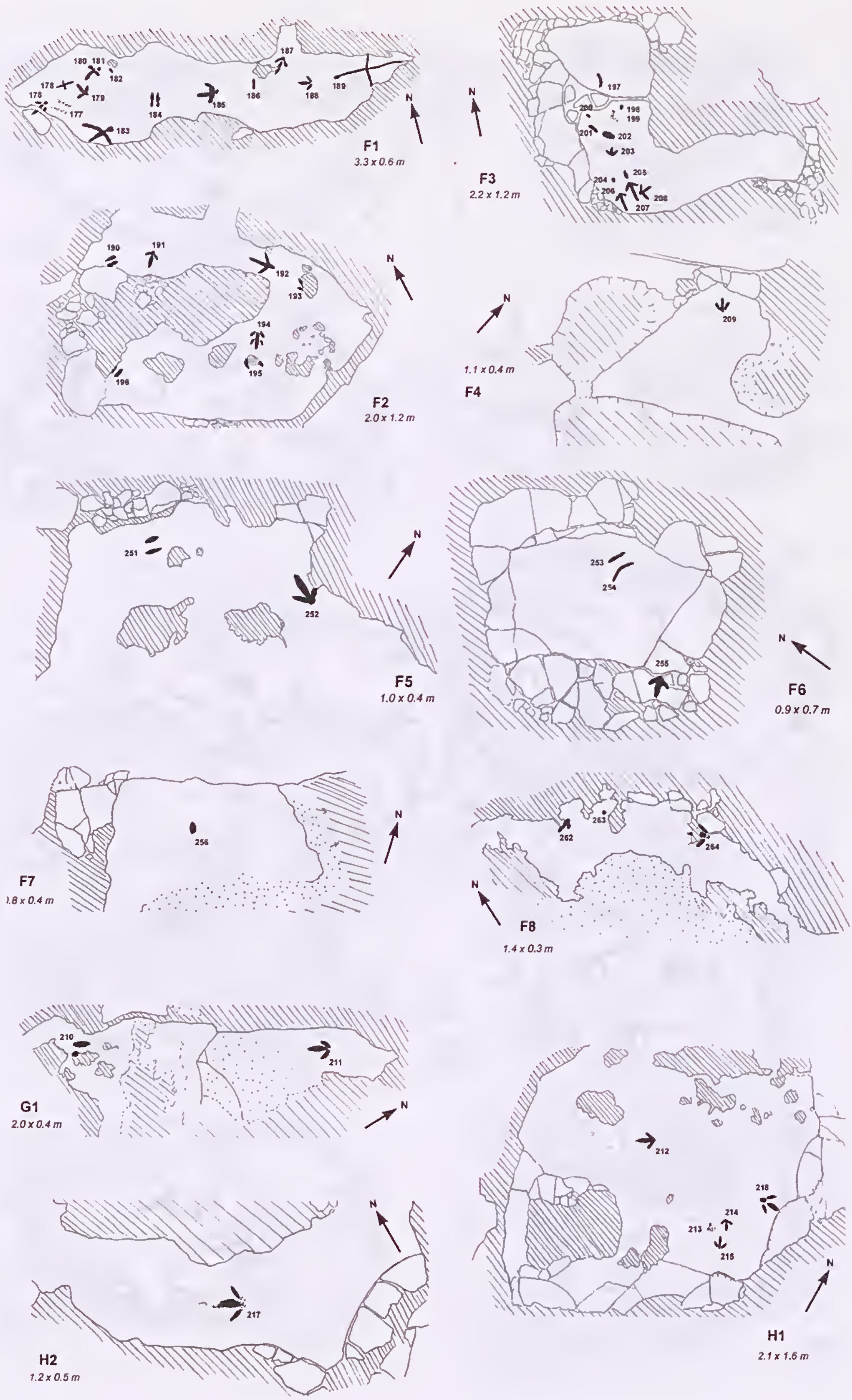
The appendix illustrates freehand sketches of all petroglyph panels showing panel designation (A1, E7, *etc*) their sizes and motif numbering.

Panel locations shown on Figure 10.




C1
large pavement
> 3 x 3 m
honeycomb
42
C2
raised strip of
smooth surface
within
honeycomb
pavement
honeycomb
43
44
45
46
D1
1.5 x 0.3 m
47
48
49
E1
1.0 x 0.5 m
50
51
E2
2.5 x 0.7 m
52
53
54
55
57
58
59
60
61
62
64
65
66
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100
101
102
103
104
266
E5
1.5 x 0.6 m
107
E6
1.1 x 1.1 m
108
109
110
111
112
N


E7
0.6 x 0.4 m
E8
1.5 x 0.5 m
E9
1.8 x 0.7 m
E10
2.3 x 0.9 m
E11
1.6 x 0.9 m
E12
0.7 x 0.5 m
E13
0.9 x 0.8 m
E14
0.8 x 0.5 m
E15
0.9 x 0.5 m
L1
0.5 x 0.4 m


F1
3.3 x 0.6 m
F2
2.0 x 1.2 m
F3
2.2 x 1.2 m
F4
1.1 x 0.4 m
F5
1.0 x 0.4 m
F6
0.9 x 0.7 m
F7
1.8 x 0.4 m
F8
1.4 x 0.3 m
G1
2.0 x 0.4 m
H1
2.1 x 1.6 m
H2
1.2 x 0.5 m


H3
1.0 x 0.8 m
218
219
220
221
222
N
H4
2.2 x 0.8 m
H5
223
224
225
226
227
228
229
230
231
232
233
234
235
236
237
238
239
N
H5
2.4 x 2.1 m
240
241
242
243
244
245
246
H4
N
J1
large slab
5 x 3 m
247
N
K1
large slab
with incomplete
grass removal
248
249
N

Journal of the Royal Society of Western Australia
A refereed journal for science in Western Australia

Instructions to Authors

The *Journal of the Royal Society of Western Australia* publishes (after refereeing)

- papers and notes dealing with original research done in Western Australia into any branch of the natural or physical sciences;
- papers and notes concerning some aspect of natural or physical science of relevance to Western Australian scientists, but not necessarily done in Western Australia;
- authoritative overviews of any subject in the natural or physical sciences with the general membership of the Society in mind;
- analyses of controversial issues of great scientific moment in Western Australia

Prospective authors of papers in the last two categories should consult the Honorary Editor for further advice. The *Journal* also publishes "Letters to the Editor" and a bibliographic summary of recent journal papers and review articles in "Recent Advances in Science in Western Australia".

Authors are encouraged to submit a list of potential reviewers in Australia or overseas, but choice of reviewers is at the discretion of the Honorary Editor. Publication in the Society's *Journal* is available to all categories of members. Submission of a paper is taken to mean that the results have not been published or are not being considered for publication elsewhere. Authors are solely responsible for the accuracy of all information in their papers, and for any opinions they express. Fifty offprints are provided free to members of the Royal Society of Western Australia; cost of offprints (including Notes) is $100 for non-members.

Manuscripts. The original and three copies must be submitted. They should be printed on opaque white paper with double-spacing throughout and have 3 cm margins. All pages should be numbered consecutively, including those carrying tables and captions to illustrations. Illustrations, both line drawings and photographs, are to be numbered as figures in common sequence, and each must be referred to in the text, in consecutive order. In composite figures made up of several photographs or diagrams, each part should be designated by a letter (*e.g.* Fig. 2B). To avoid risk of damage to the original figures, authors should retain the original figures until the paper is accepted. The copies of the figures accompanying the manuscript must be of good quality. Authors are advised to use the most recent issues of the Journal as a guide to the general format and bibliographic style of the manuscript, and to conform as closely as possible to the style in preparing the manuscript. Authors should maintain a proper balance between length and substance, and papers longer than 10000 words would need to be of exceptional importance to be considered for publication. Electronic processing of manuscripts from disks supplied by the authors is necessary to reduce publication costs. Following acceptance and editing of the manuscript, authors should amend their manuscript and forward one printed copy of the paper and the word-processing file on computer. Preferred format for manuscript files is a doc or rtf file. Templates (rtf and Word format) for manuscripts are available on the Royal Society of Western Australia web page (http://www.rswa.org.au). Manuscripts may also be submitted electronically to rswa_ed@iinet.net.au

Notes. The Society wishes to encourage scientists to publish short notes dealing with original research done in any branch of the natural or physical sciences in Western Australia, or concerning some aspect of natural or physical science of relevance to Western Australian scientists. The objective in publishing Notes is to encourage the dissemination of research findings that might not be enough for a full paper but nevertheless be of interest to other scientists, especially those in Western Australia. In addition, specific aspects of student theses, particular findings of commissioned reports, or isolated observations of significance might be well presented as a one or two page note. Notes will be restricted to a maximum length of two printed pages; notes are particularly sought as these often ensure full use of the pages available in each issue. They should generally have an Abstract, Introduction, Methods, Results and Discussion, and References sections, but the exact section organization is flexible. Photographs and figures should be suitable for single column reproduction (82mm wide) wherever possible. Manuscripts submitted as a Note will be reviewed in the same manner as full articles. Templates (rtf and Word format) for notes are available on the Royal Society of Western Australia web page (http://www.rswa.org.au).

The **Title** should begin with a keyword. The **Abstract** should not be an expanded title, but should include the main substance of the paper in a condensed form. The metric system (S.I. units) must be used. Taxonomic papers must follow the appropriate International Code of Nomenclature, and geological papers must adhere to the International Stratigraphic Guide. Spelling should follow the Concise Oxford Dictionary. **Keywords** or phrases should be provided (maximum of eight, or two printed lines).

References must be set out as follows, with journal titles spelled out in full;

Paper:	Jackson A 1931 The Oligochaeta of South-Western Australia. Journal of the Royal Society of Western Australia 17: 17-136.
Book:	Jacobs M R 1955 Growth Habits of the Eucalypts. Forestry Timber Bureau, Canberra.
Chapter in Book:	Dell J 1983 The importance of the Darling Scarp to fauna. In: Scarp Symposium (ed J Majer). Western Australian Institute of Technology, Bentley, 17-27.

Illustrations. High quality illustrations are required, no larger than 300mm x 400mm, with sans serif lettering suitable for reduction to appropriate publication size (82 or 168 mm wide). Scale must be indicated on illustrations. Photographs must be good quality prints, not exceeding 168mm x 252mm. Colour plates may be published, at the discretion of the Honorary Editor, if these are considered important for clarity or precision of description. Additional printing costs such as those for colour blocks or folding maps may be charged to authors, according to economic circumstances at the time. Please consult the Honorary Editor. It is preferred that figures be also provided as high quality computer graphic files (*e.g.* tif, gif, jpg, cdr or eps files) to ensure high quality reproduction.

Supplementary Publications. Extensive sets of data, such as a large Table or Appendix, may be classed as a Supplementary Publication and not printed with the paper but lodged with the Society's Library (held in the Western Australian Museum, 49 Kew Street, Welshpool, WA 6106) and with the National Library of Australia (Manuscript Section, Parkes Place, Barton, ACT 2600). Photocopies of a Supplementary Publication may be obtained from either institution upon payment of a fee.

Contributions should be sent to:
The Honorary Editor, Journal of the Royal Society of Western Australia
PO Box 7026, Karawara, Western Australia 6152
or email to rswa_ed@iinet.net.au

The Journal of the Royal Society of Western Australia© is published quarterly by:
The Royal Society of Western Australia, PO Box 7026, Karawara, Western Australia 6152.
rswa@museum.wa.gov.au

This part was edited by M Brocx & K Meney

Registered by Australia Post — Publication No. PP642409/00008.

Claims for non-receipt of the Journal should be submitted within 12 months of publication, to:
The RSWA Librarian, PO Box 7026, Karawara, Western Australia 6152,
or email rswa@museum.wa.gov.au
Address changes should be submitted to The Hon. Membership Secretary,
PO Box 7026, Karawara, Western Australia 6152.

Published on 19/12/2011 **Typeset and printed in Western Australia**